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Shadow Casting Phenomena at Newgrange

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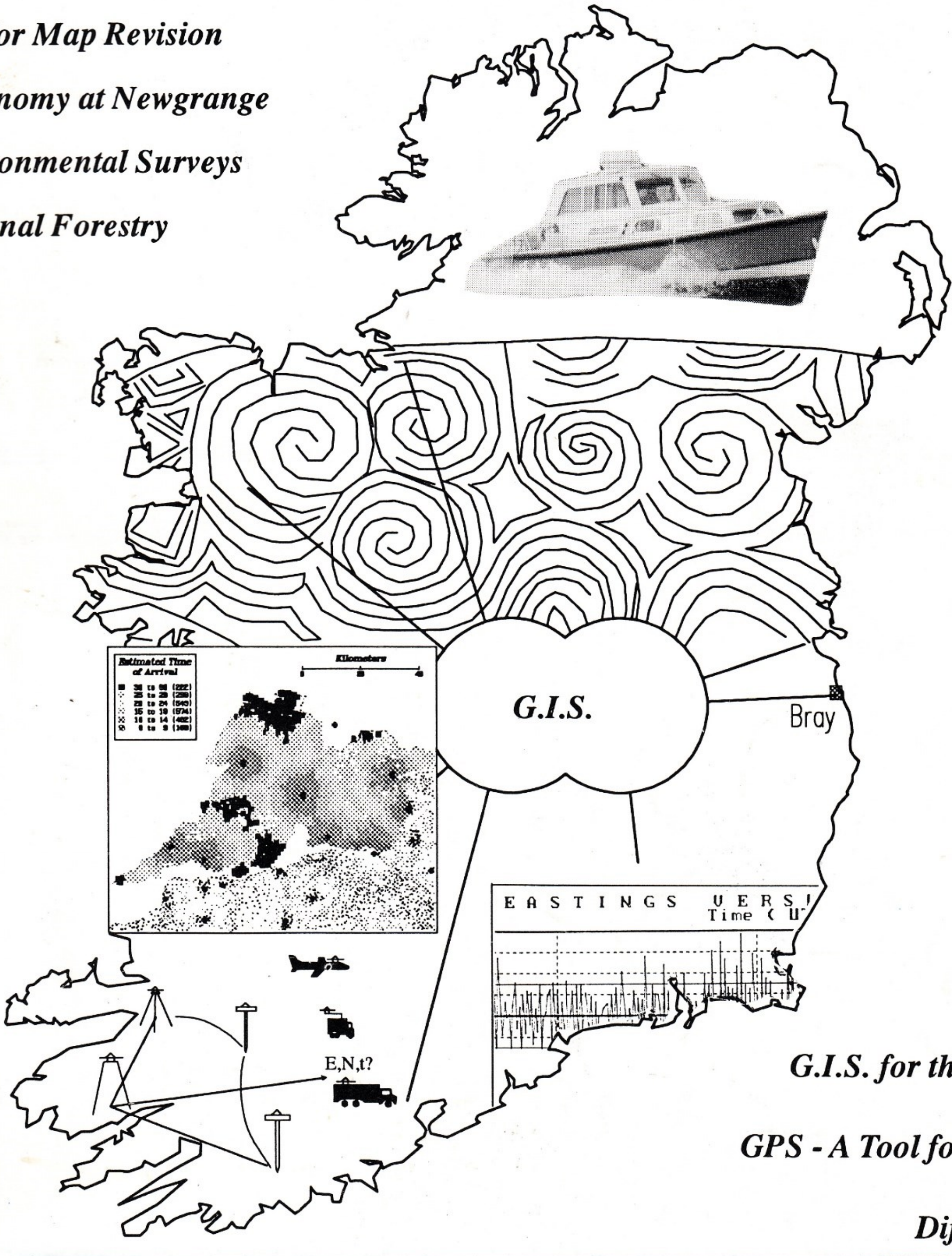

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Preface

Shadow Casting Phenomena at Newgrange is the title of a paper first read to the annual conference of the Irish Society of Surveying Photogrammetry and Remote Sensing held in Trinity College Dublin, April 1991.

This e-version is an author copy of that paper providing the opportunity to make descriptive additions, revisions and minor corrections to the original work. The original 35 mm photographic slides recorded in 1986–1989 for illustration purposes are reproduced using Digital Macro Photography and image post-processing with Adobe Photoshop Lightroom Classic CC 7.3.1 Release (Licensed to TU Dublin). The paper draws on an MSc by Research (1990) awarded by the School of Civil Engineering, Trinity College Dublin. The author is a professional geodetic surveyor specialising in field astronomy and holds a PhD (2011) awarded by the School of Archaeology, University College Dublin.

Field surveying for the project was carried out with the permission and support of the Office of Public Works and Ms. Clare Tuffy, manager of the Brú na Bóinne Visitor Centre.

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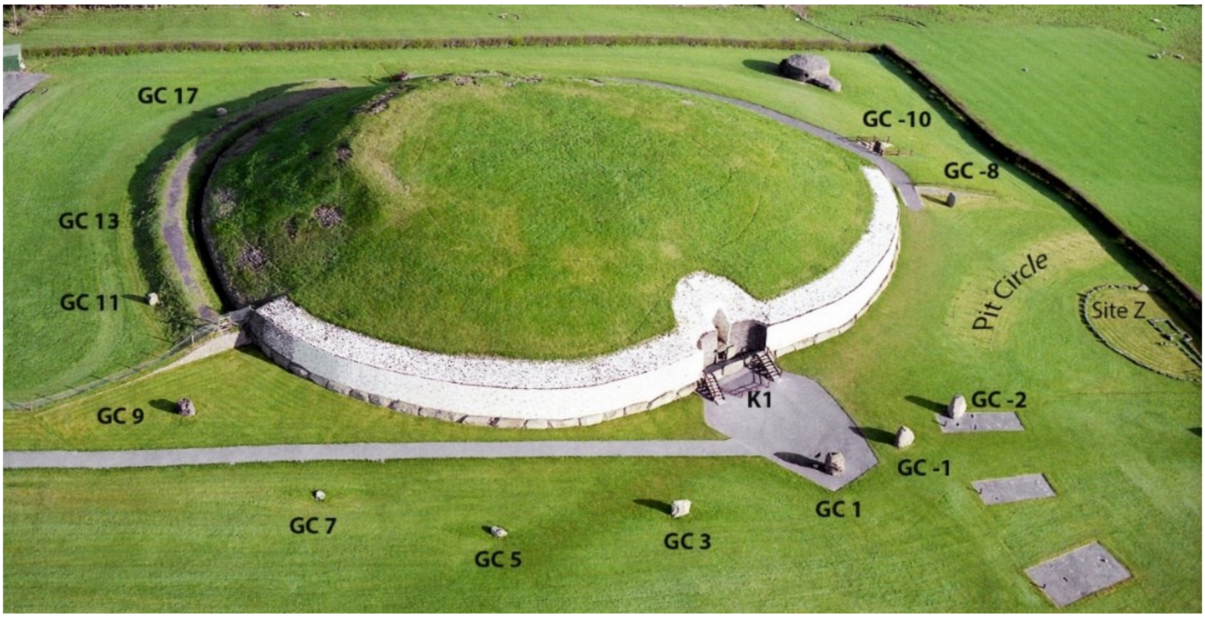
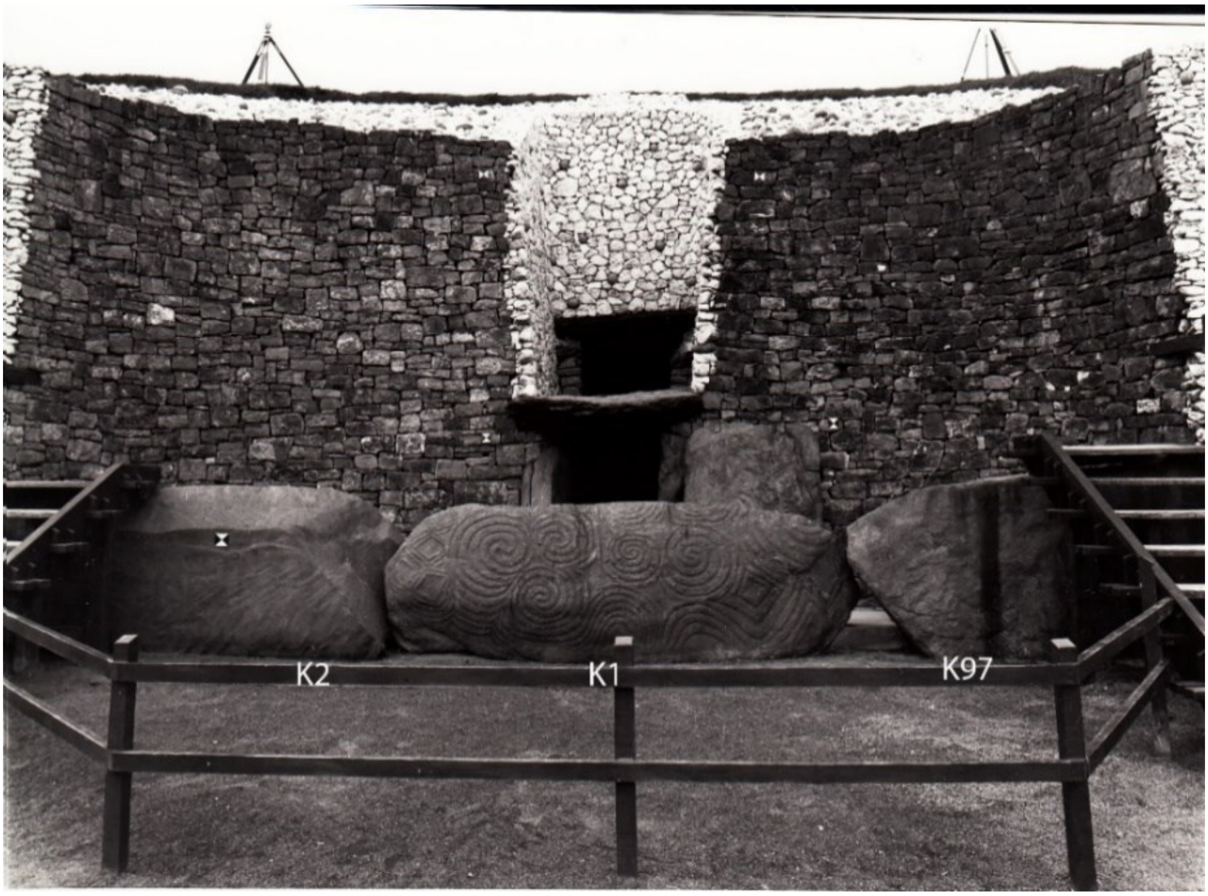
Newgrange passage tomb



This aerial view of Newgrange passage tomb is looking north and shows the cairn, delimiting kerbstones, the reconstructed quartz and granite facade, and the enclosing ring of twelve monoliths coded with the prefix GC, meaning Great Circle. The irregular numbering system was devised by the excavation director, Prof. Michael J. O'Kelly, to allow for any future discovery of sockets indicative of missing stones. None have been found to date. The remains of passage tomb Z (Site Z) and the trace of a circular Early Bronze Age pit circle which transects the socket of GC−2 are visible on the right-hand side of the image. Shadows cast by the monoliths in this illustration are foreshortened by the mid-morning aspect of the elevated Sun in comparison to the considerably longer shadows evident soon after dawn. Annotations are by the author.

Newgrange passage tomb facade and entrance



This image is the left-hand photograph of a stereoscopic pair used to photogrammetrically survey and digitally model the Newgrange passage tomb facade in 1988. Photo-control targets used to scale the digital model in three dimensions appear in the image. Visible archaeological detail includes the reconstructed entrance facade of granite and quartz blocks, the richly embellished entrance kerbstone K1, the three-spiral motif on the left side of the central vertical groove on K1, the lintelled entrance and door-stone on the right of the entrance, and the roof-box structure above the entrance lintel stone. This unique slot-opening enables direct light from the rising Sun on winter solstice to penetrate to the rear of the cruciform burial chamber located *c*. 19 m inside the cairn.

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Shadow casting from monolith GC-1 onto the entrance kerbstone K1

This image shows the entrance and door-stone to Newgrange passage tomb and shadow casting by monolith GC−1 onto the vertical face of the entrance kerbstone K1. As the climbing Sun increases in altitude and azimuth after dawn, this shadow tracks diagonally downwards across the three-spiral motif, reaching ground level on the right-hand side of the central vertical groove at the top of the kerbstone. The phenomenon recurs biannually and can be observed crossing the width of the motif for *c*. 20 minutes over 10 days on 15–24 February and again on 18–27 October when the astronomical declination of the Sun is centred on *c*. −12°. The shadow depicted in this image is a graphic reconstruction from a photograph recorded on 1989 February 2 (see Figure 7 in the following paper).

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Shadow Casting Phenomena at Newgrange

F. T. Prendergast

Abstract: *A digital model of the Newgrange passage tomb and surrounding ring of monoliths known as the Great Circle is used to investigate sunrise shadow casting phenomena at the monument. Diurnal variation in shadow directions and lengths are analysed for their potential use in the Bronze Age to indicate the passage of seasonal time. Computer-aided simulations are developed from a photogrammetric survey to accurately show how three of the largest monoliths, located closest to the tomb entrance and archaeologically coded GC1, GC−1 and GC−2, cast their shadows onto the vertical face of the entrance kerbstone, coded K1. The phenomena occur at astronomically interesting declinations, consistent with possible seasonal observance of the rising Sun at key dates in the Bronze Age when the Great Circle was constructed. The analysis further shows how the dominant three-spiral motif on K1 is repeatedly targeted by shadow casting on these dates, making this artistically elaborate motif focal. This could indicate the positioning of GC1, GC−1 and GC−2 enabled users in the prehistoric past to predict and mark seasonally different periods of ceremonial or ritual importance. The investigation further reveals that GC3 casts a shadow onto the base of GC5 on dates which are compatible with the proposed low-precision calendrical model. The cycle of shadow casting is considered to commence and end at winter solstice. Recorded site photography verifies the computer simulations and provides visualisations for archaeological record.*

KEYWORDS: archaeoastronomy; Boyne Valley; climate history; megalithic art; Newgrange; passage tomb; shadow casting; stone circle; winter solstice

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Introduction

Newgrange passage tomb, Co. Meath, in east Ireland (latitude +53°.6947, longitude -6°.4756) is situated on a low glacial ridge fourteen kilometres west of the coastal town of Drogheda. The elevation of the ridge is *c.* 55 m above mean sea level affording a commanding view of the River Boyne and its flood plain one kilometre to the south. The monument consists of a large round kerbed cairn with an entrance passage in the south-east sector leading to an internal cruciform burial chamber. Four smaller passage tombs are located on the same ridge, sites K and L to the west and sites Z and Z1 to the east. Additional Neolithic and Bronze Age structures (passage tombs, cairns, megalithic structures and enclosures) are distributed between the ridge and river. The cairn is encircled by twelve monoliths which vary greatly in their spacing, distance from the kerb and height above ground level (Figure 1).

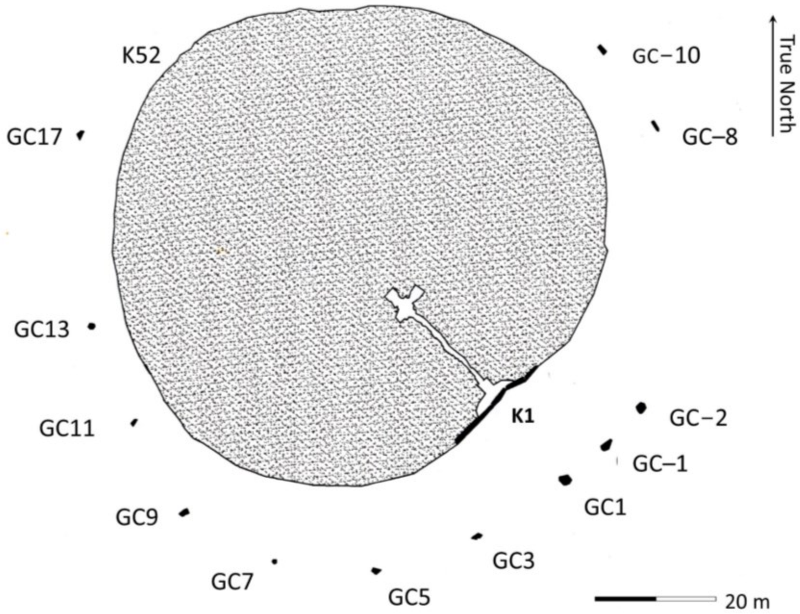

Fig. 1. Plan of Newgrange passage tomb and Great Circle monoliths.

(Surveyed 1988 September 23, F Prendergast)

Neolithic tombs in Ireland are typologically termed court, portal or passage and were built during the fourth and early third millennia BC. The passage type, one of which is the subject of this paper, is characterised by a round mound of turves and stones delimited by contiguous kerbstones. Entry to the burial chamber is *via* the passage formed by side orthostats roofed with relieving stone lintels. Chamber shapes are undifferentiated (no distinction between the passage and the chamber), round, polygonal or cruciform. The cruciform chamber is the most developed having three recesses, often with a basin stone receptacle containing human cremated remains.

Passage tombs are frequently situated on high ground in dense or distributed clusters; some are isolated. Location on high ground offered vantage and intervisibility and these attributes may have held additional meaning for their communities (Herity 1974). The axial orientation of some tombs are also known to be astronomically aligned towards the rising or setting Sun at key times in the year such as the solstices (Patrick 1974a). This paper describes investigations carried out by the author at Newgrange in the late 1980s into seasonal sunrise shadow casting phenomena by monoliths GC−2, GC−1, GC1, GC3 and GC5 prominently clustered at the front of the tomb (see Figure 1).

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Summary description of Newgrange passage tomb

The Newgrange cairn is non-circular in plan with diameters ranging from 78.6 m in a north-west to south-east direction to 85.3 m in a north-east to south-west direction (see Figure 1). The height of the cairn is 10.9 m–13.4 m above the summit of the ridge (O'Kelly 1982, 21). The bulk of the material in the mound consists of medium-sized water rolled stones, has a volume estimated by Prof. Michael J. O'Kelly at 200,000 tonnes and a construction period of 16–30 years (*ibid*. 117–118). The entrance kerbstone is designated K1 and the archaeological coding of the remainder increments in a clockwise direction to K97. Both K1 and K52, diametrically opposite K1, are the most elaborately decorated of the kerbstones with K1 fully covered in intricate megalithic art. The axis-line joining K1 to K52 runs through the burial chamber and symmetrically divides the cairn. These same kerbstones have short central vertical grooves which run over their tops – a feature additionally found on the east and west entrance kerbstones at the nearby Knowth passage tomb. O'Kelly suggested these grooves highlighted the 'specialness' of the entrance kerbstones to the tomb builders (*ibid*. 72).

The entrance passage of Newgrange tomb runs into the cairn in a north-west direction for *c*. 19 m. This was likely sealed by the door-stone now positioned on the right-hand side of the entrance as the tomb is entered. The roof-box structure above the entrance was discovered by O'Kelly in 1963 during restoration of the monument. The likely purpose of this slot-opening was to enable the rising Sun illuminate the passage and chamber for a period symmetrically centred around the day(s) of winter solstice (Figure 2). The astronomer Douglas C. Heggie claimed that if this orientation was deliberate then Newgrange is the oldest astronomically orientated megalithic structure known before 3000 BC (Heggie 1981, 214).

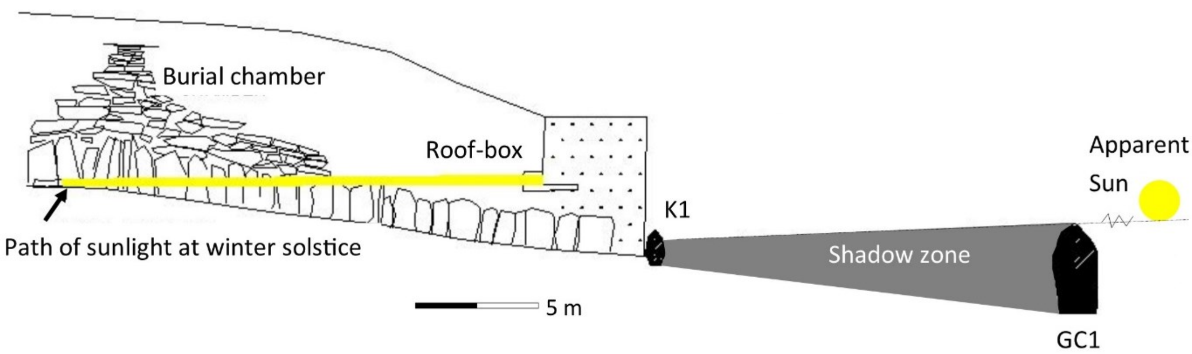

Fig. 2. Section through the Newgrange cairn and Great Circle looking north-east (after O'Kelly 1982, Fig. 4, with additions).

Newgrange 'Great Circle'—a description

A ring of monoliths termed the 'Great Circle' by O'Kelly surrounds the Newgrange cairn (see Figure 1). Parallels for passage tombs being surrounded by a stone circle are to be found in Scotland (e.g. Lewis 1900). At Newgrange, the pitch (consecutive spacing) between the twelve extant stones is irregular. It was thus O'Kelly's belief that the ring was incomplete and, if ever complete, could have accommodated between thirty-five and thirty-eight stones. However, he found no evidence in his excavations for this and his uneven archaeological coding, used here, made provision for any possible future discovery of sockets indicative of missing stones. Importantly, he wrote: 'It must be stressed, however, that very little evidence was forthcoming in the excavated areas for the original presence of these missing stones and the system of numbering must not be taken as anything other than a convenience for excavation purposes' (O'Kelly 1982, 79). He further stated 'The matter is of course

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highly speculative and it has been gone into in some detail only because of the present interest in the mathematical and astronomical possibilities which are alleged to be inherent in these structures’ (*ibid*. 79). These issues are the main focus of this paper.

Three of the monoliths prominently located opposite and east of the entrance to the tomb are decidedly the largest in the ring, more evenly spaced, and most conspicuous and dramatic to the eye (see Figure 1). The monolith nearest to K1, being almost collinear with the axial direction of the passage into the tomb, is thus coded GC1. O’Kelly devised this numbering convention to give those in a clockwise direction from GC1 a positive code and those in an anti-clockwise direction from GC1 a negative code. None bear megalithic art, a decorative tradition characteristic of the Neolithic. Monolith GC5, consecutive to GC3 in the ring, is a mere 0.5 m above ground level and this height is generally accepted as the original height of the stone (see Figure 5e). Overall, and despite extensive archaeological investigation at the site to date, additional stone sockets have not been found and scientific thinking on the purpose of the Great Circle remains inconclusive. One of the aims of this paper is to advance the discussion on this question.

Chronology of the passage tomb and Great Circle

The chronological relationship between the passage tomb and the Great Circle was a matter of considerable importance to O’Kelly. On this he wrote: ‘Two facts are certain: the first is that the circle was erected before the main cairn had collapsed – this is clear from the way in which the cairn slip has mounded up against the existing stones’; and: ‘The circle, therefore is not later than the Beaker-horizon[1], dated at Newgrange to 2000 bc, and it may be contemporary with or earlier than the cairn’ (*ibid*. 82). Radiocarbon dating, first carried out by O’Kelly and later by another archaeologist in the 1980s, ultimately resolved the relative chronology of the tomb and the Great Circle.

Chronology

Eleven dateable samples procured from the cairn and tomb were radiocarbon dated for O’Kelly. Two of these were dated using samples of caulking obtained from between the roofing slabs of the burial chamber (GrN-5462-C and GrN-5463). Each provided a building date for the Newgrange tomb estimated as 2475 ±45 bc and 2465 ± 40 bc respectively, measured in radiocarbon years (*ibid*. 230–31). When calibrated into calendar years annotated as BC, the construction date for the tomb is *c*. 3200 cal BC. Separately, the central date for the Late Neolithic/Beaker-period phase of occupation at Newgrange provided by O’Kelly is 2000 bc or 2500 cal BC (*ibid*. 12), affirming continuity of settlement at the site over many centuries. This observation has relevance to argument made later in this paper.

In 1985, David Sweetman (1985) re-opened an area of ground previously excavated by O’Kelly to establish whether a pit and post enclosure, first discovered by O’Kelly, continued through and underneath the path of the Great Circle. O’Kelly had previously discovered trenches associated with the enclosure which he showed to be running up to the west and east sides of GC−2 but not underneath it. Sweetman re-excavated ground at the base of the west and south faces of GC−2. In Cutting 5 he re-located the ends of the same trenches discovered by O’Kelly but found these to be ‘running under the stone’. He also found the base of GC−2 stood above the level of the rims of nearby burial pits. Several of these contained fragments of flint, cremated bone and charcoal samples, radiocarbon dated to 2015 ±65 bc. Sweetman concluded that because the base of GC−2 lay above the rim of a pit whose contents post-dated the construction of the nearby Newgrange cairn, the cairn and

[1] The Beaker culture is a term used to describe Late Neolithic and Early Bronze Age communities characterised by bell-shaped beakers, a distinctive type of pottery often found buried as prestige objects along with cremated human remains.

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Great Circle must have been the result of two distinct phases of development and occupation. Sweetman proposed that the erection of the monoliths had to be later than the Beaker phase and could not, as a result, be earlier than *c*. 2015 bc which is *c*. 500 years later than the date accepted for construction of the passage tomb. These findings are applied and considered in the analysis of shadow casting phenomena presented in this paper.

Cairn slip, Great Circle and shadow casting

Solar shadow casting onto K1 by any of the Great Circle monoliths implicitly requires intervisibility between the shadow caster, or gnomon, and a target surface. Archaeological excavation shows how a portion of the mound frontage suffered a catastrophic collapse at an unknown date in prehistory (O'Kelly 1982, 68–73). It is described as a two-phase collapse, the latter being: 'a sudden great slide of stones' extending 'outwards as far as the great circle in the area opposite the tomb entrance and well beyond the circle at the east and west sides where the circle is nearer to the kerb'. This is illustrated using profiles (sections) drawn radially outwards from K95 and K96 (O'Kelly 1982, Figs. 6A and 6B). These show cairn material extending out to cover part of the pit circle. Explicitly, the front portion of the kerb including K1 would certainly have been buried, impeding intervisibility between the Great Circle and the kerb. This suggests that if specific monoliths were erected for the purpose of shadow casting onto K1 in particular, the collapse of the cairn must have post-dated construction of the Great Circle. Expressed differently, the shadow casting hypothesis contends that the passage tomb pre-dated construction of the Great Circle, and the cairn slip post-dated construction of the passage tomb and the Great Circle.

Astronomical alignment of the passage tomb

Evidence of solar astronomical alignment at Newgrange in the Neolithic is described here to establish a cultural context for such a tradition possibly continuing into the Bronze Age when the ring of monoliths was erected. Sir Joseph Norman Lockyer, an English astronomer, provided the first probable scientific reference to such an alignment. Writing on prehistoric burial tombs in Britain, he stated: 'Of them all Bryn Celli Ddu is the most interesting, as there is a long allée courverte or creep way, which is exceptional in Britain, so far as ''cromlechs'' go, though many may be still hidden in "long barrows" such as New Grange, which, so far as I can make out, is oriented to the Winter Solstice.' (Lockyer 1909, 430). The following interpretation by the author can explain Lockyer's deduction.

Lockyer (*ibid*. 432–33) cited a plan drawing of the Newgrange cairn and tomb by William Copeland Borlase who compiled 'The Dolmens of Ireland' (Borlase 1897, 350, Figure 333). Borlase credited that plan to the archaeologist George Coffey who published it some years earlier (Coffey 1892–1896, 4, Figure 2). An examination of the orientation of both drawings (they are the same plan) shows the azimuth (true bearing) of the passage axis to be *c*. 132°. This falls within 2° of the azimuth of the central axis of the passage as first measured in modern times by the surveyor Jon Patrick (1974b). Importantly, magnetic north in 1890 was *c*. 21° west of true north. Had Coffey used magnetic north to orientate his plan, this would have been clearly evident because of the gross angular difference between true and magnetic north pertaining at that time. Lockyer is not known to have ever visited the monument but his astronomical expertise, and eye, would have allowed him to 'make out' the winter solstice alignment of Newgrange merely by examining the south-east direction of the passage relative to the direction of true north shown on Coffey's plan, later adopted by Borlase.

More than seventy years after Lockyer published his observation, Claire O'Kelly, the wife of Prof. O'Kelly, described a belief or tradition in the locality of Newgrange that the rising Sun, at some unspecified time, illuminated the three-spiral motif on the vertical face of stone C10 on the right-hand side of the end recess within the cruciform burial chamber (O'Kelly 1978, 111). The hidden aspect of this stone, however, prevents any direct illumination by the rising Sun. Regardless, when Michael O’Kelly began to think about it, and because of the south-easterly orientation of the entrance passage, he thought a visit to the chamber at winter solstice would be justified. On 21 December 1969 he made the empirical discovery, in modern times, of the now famous winter solstice sunrise alignment (O'Kelly 1982, 123–24). Patrick (1974b) subsequently undertook an archaeoastronomical survey for O’Kelly and concluded that illumination of the burial chamber was of low precision, occurring when the azimuth of the Sun was between the limits 133° 42′ and 138° 24′. For an angular altitude of the indicative local horizon of 0° 55′ ±2′, the range in astronomical declination[2] corresponding to Patrick’s azimuth limits is −22° 58′ to −25° 53′. Patrick reported the widest azimuth and declinations limits of the roof-box, akin to field of vision, leading Heggie (1981, 213) to be sceptical of Patrick’s claim for an intentional solstitial alignment of the tomb (see Statistical Analysis section).

The astronomer Tom Ray (1989) reviewed Patrick’s calculations in a subsequent measured survey of the passage, chamber and roof-box. He found:

- Patrick’s upper azimuth limit was 1° too high and his declination window was also too high and should be reduced accordingly;
- the roof-box was very probably designed in width, height and with astronomical alignment intent;
- direct sunlight can now penetrate only to the rear edge of the burial chamber but could have reached the back-stone in the end recess of the cruciform chamber in Neolithic times due to the different tilt of the rotation axis of the Earth, termed obliquity ε[3].

Ray’s findings improved the probability of intentional solstitial alignment of Newgrange passage tomb and, relevant to the investigation of the Great Circle undertaken in this paper, the possibility that other light and shadow manifestations might be embedded in the broader archaeology and calendrical function of both monuments.

Prehistoric solar calendar?

The archaeologist Euan MacKie (1988, 211–12) argued that Neolithic farmers would have marked the seasons and the passage of time by simple observance of the apparent movement of the Sun along the horizon (see Figures 9a and 9b). This amounts to a most obvious change in azimuth of *c*. 87° between winter and summer solstice for the latitude range of Ireland, the so-called solar-arc. He further maintained that the axial alignment of Newgrange on winter solstice sunrise demonstrated an understanding of a basic calendar in the Neolithic, knowledge of which must have preceded construction of the passage tomb. This awareness may have been tied to the timing of crop planting,

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[2] The position of any star on the celestial sphere is partly defined by its declination angle δ measured from the celestial equator and is analogous to latitude on earth (Bomford 1980, 257). Declination values can act as an indicator of the time of year *e.g*. the arc of the Sun’s diurnal passage in the sky is lowest at the winter solstice (δ ≈ −24° in the Neolithic and Bronze Age), highest at summer solstice (δ ≈ +24° in the Neolithic and Bronze Age), and can have values anywhere between these limits, including δ ≈ 0° at the equinoxes. The values of δ reported in this paper are to the nearest minute of arc for computational consistency. However, such precision is unnecessary for data interpretation purposes. Furthermore, a declination which approximates to 0°, and the term ‘equinox’, are regarded in this paper as interchangeable for the low level of precision being considered.

[3] Obliquity is the angle between the planes of the Earth’s equator and the ecliptic, 23° 26' in the current epoch (*ibid*. 257). In *c*. 3200 BC, when the Newgrange cairn was constructed, obliquity was 24° 02'. In 2500 BC, when the Great Circle monoliths were erected, obliquity was 23° 59' (Berger 1976, Berger 1977). Accordingly, sunrise and sunset directions were then a little more than 1° (about two solar diameters) more than their present azimuthal limits at the solstices. This effect is related to the slow long-term secular variation in obliquity.

the harvest and for predicting and marking times for ceremonies and rituals. It is therefore legitimate to suggest that selected monoliths surrounding Newgrange could have marked important seasonal divisions of the year during the Beaker-period phase of occupation, indicated by the alignment of their shadows at such auspicious times. Relevantly, the observed shadow cast by GC1 onto the vertical face of K1 at winter solstice, as next described, provided the idea and motivation for this investigation.

In August 1986 the author participated in a photogrammetric survey to map the corbelled roof in the eastern burial chamber of the nearby passage tomb at Knowth, Co. Meath. That work was commissioned by Prof. George Eogan, the excavation director. During the survey, Clare Tuffy, manager of the visitor centre at Newgrange, extended an invitation to visit the monument on the following winter solstice. On 20 December 1986, the author was present to observe the rising Sun illuminate the burial chamber as first recorded by O’Kelly in 1969. It was Tuffy who first drew my attention to the shadow casting phenomenon outside the passage tomb. The phenomenon had been earlier described by the artist Martin Brennan (1983, 76–77). This was photographically recorded and is described below.

Shortly after local sunrise, *c*. 09:00 UTC[4] on 20 December, 1986, the tip of the shadow cast by GC1 was observed moving diagonally down across the face of the entrance kerbstone K1. It tracked tangentially beneath the prominent three-spiral motif on the left side of that stone. The phenomenon lasted for about 20 minutes (see Figure 6). This will only occur at winter solstice when the fully risen Sun, *i.e*. lower limb on the horizon, reaches the extreme azimuthal limit of *c*. 134° in the south-east. Before/after winter solstice, the shadow’s trajectory is across the face of kerbstone K2 on the left side of K1. This empirical observation immediately suggested to the author that shadow casting by adjacent monoliths in the Great Circle might harbour similar calendrical potential for marking the passage of seasonal time. The initial idea developed into a working hypothesis to be methodologically tested using computer simulation followed by on-site photographic recording for calibration and verification purposes (see Figures 6–9). As a prerequisite to investigating the shadow hypothesis, the first-ever spatial analysis of the Great Circle was undertaken. This was considered necessary so as to address what O’Kelly had previously described as the prevailing interest in the highly speculative mathematical and astronomical possibilities alleged to be inherent in the monolith locations.

Field survey to digital model

The investigation method used field survey techniques, mathematics and computer simulation to analyse circle geometry/morphology and model the directions and times of shadow casting. This method replicated, in part, earlier surveys by Patrick and Ray in determining declination limits and indicative calendrical dates of the phenomena of interest. What is novel here is the use of digital simulation to first identify and then predict shadow casting at the Great Circle. The results could then be photographically recorded to verify the digital modelling method and create an evidence-based archive for archaeological record. The research stages are listed below and then summarily described.

- field survey;
- photogrammetric survey;
- digital modelling;
- geometrical analysis of the Great Circle;
- shadow casting simulation;
- photographic verification;
- digital block shifting of monoliths;
- statistical analysis for probability;
- discussion;
- conclusions.

[4] UTC (Coordinated Universal Time) is the basis of international civil timekeeping and replaced GMT in 1972.

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Field survey

The field survey stage established a network of intervisible control stations located around the base of the cairn. These were connected by a closed-loop traverse calculated on a local grid coordinate system to map the relevant archaeological elements – facade features, kerbstones adjacent to K1 and all monoliths. The y-axis of the grid was astronomically aligned to the local meridian using a gyroscopic theodolite (Wild GAK-1) with an absolute accuracy specification of ±20”. The gyroscopic attachment features an internal powered suspended spinning rotor which precesses in the horizontal plane about the local meridian with damped simple harmonic motion. This capability makes it meridian-seeking. The relative x, y, z coordinates of the network of survey stations were determined with a digital theodolite and infrared distance meter positioned over each traverse station, yielding object point coordinates with a standard error of less than one centimetre. Each monolith was modelled from polars (azimuths and distances) observed onto key surface points to provide accurate wire-frame representations (see Figures 5a–5d). The facade of the passage tomb and kerbstones nearest the entrance were digitally mapped by photogrammetry because these structures were either inaccessible for contact measurement purposes or, as in the case of K1, had inscribed megalithic art considered too intricate to capture by conventional measurement procedures.

Photogrammetric survey of the Newgrange facade

Photogrammetry is a non-contact process suitable for measuring inaccessible or irregularly shaped objects. The 3D coordinates of points of interest in the field of vision can be determined provided these appear in at least two photographic images recorded from different camera positions. Therefore photography for photogrammetric mapping must be acquired as overlapping pairs. If the photographic pair are separately mounted in a stereo-comparator, objects are then viewable in 3D for measurement purposes.

The technique used here is based on the Direct Linear Transformation (DLT) method developed by Abdel-Aziz and Karrara (1971). DLT uses co-linearity equations to relate the spatial position of a point(s) to its imaged position on the photograph. This is only possible where a minimum of six control points are common and visible in each image. Accordingly, the x, y, z values of six control targets were determined in the local ground coordinate system described earlier. Software developed by Mooney (1988) to implement the DLT method was used to acquire the coordinates of a sufficient number of object points to model surface detail on the Newgrange facade and kerbstones K1, K2, K3, K96 and K97 located around the entrance to the tomb.

For photogrammetry fieldwork, a Bronica non-metric camera with C120 film imaged two sets of stereo-pairs of photographs. The closest stereo-pair allowed the complex detail on the obverse face of K1 to be measured in 3D. The second stereo-pair captured detail on inaccessible sections of the entrance facade. The digitised coordinates of the facade and the megalithic art on K1 were then merged with the coordinates of the monoliths, creating a single total digital model. This was comprised of facade architectural detail, the surfaces of the five kerbstones nearest the tomb entrance, and the surfaces of the Great Circle monoliths (see Figure 5a).

Digital modelling

The text-file of coordinates obtained by photogrammetry was re-formatted as an AutoCAD drawing file for the next stage of the investigation. AutoCAD is a commercial computer-aided design and drafting software application (Autodesk 1986). Digital simulation of naturally occurring shadow casting, described later, was implemented using pre-calculated celestial coordinates of the apparent path of the Sun in the astronomical horizon system. These were compiled for user-specified dates and at five-minute intervals of time spanning thirty-minutes after local sunrise. This captured the diurnal beginning and end of the phenomena on any desired morning of interest (see Digital Simulation of Shadow Casting).

Geometrical analysis of the Great Circle

An analysis of the morphology of the Great Circle was considered important to the overall investigation and shadow casting hypothesis. As mentioned, O’Kelly had entertained ‘the mathematical and astronomical possibilities’ allegedly inherent in the monoliths (O'Kelly 1982, 79). Spatial analysis, as a technique, had the potential to discover if intentional circular form was a deliberate design feature of the Great Circle. If the investigation failed to detect this, then the shadow casting hypothesis could be given greater weight. A detailed description of this analysis is given in the section *Geometrical Analysis of the Great Circle*.

Shadow Casting

A shadow is the area of darkness formed on a surface when the casting object, a gnomon, intercepts light falling on that surface from a source (Oxford University Press 1984). If the source is the Sun, the shadow has two distinct regions, one of full-shadow termed the umbra and the other of half-shadow termed the penumbra which fringes the umbra. Only the umbra is of interest here. Instantaneous umbral shadow path is determined by the slope of the tangent (path) joining the tip of the shadow, the top of the gnomon and the lower limb of the apparent disc of the climbing or descending Sun (see Figure 2). The term ‘apparent’ takes the significant bending effect of atmospheric refraction into account for modelling purposes when the Sun is very close to the horizon. The instantaneous direction (alignment) of a shadow is correlated with change in the azimuth of the Sun over time. The method used in the analysis is explained in the section *Simulation of Shadow Casting*.

Photographic verification

A photographic record of the phenomena predicted in the computer simulations was obtained over a three-year period. This was necessitated by the requirement for cloud-free conditions at sunrise. The resulting images calibrated and verified the accuracy of the digital modelling method and provided a photographic archive for archaeological record (Prendergast 1990). A selection of those images are featured in the Results section (see Figures 6–9).

Geometrical analysis of the Great Circle

Newgrange cairn has a basal circumference of 253 m. If the purpose of the Great Circle was merely to surround or enclose the cairn and tomb, the number of monoliths greater than the twelve extant would be expected. Furthermore, the pitch between successive stones, and the gap as measured orthogonally from each monolith inwards towards the kerb, would also be expected to show equivalence for likely aesthetic reasons, perhaps important to the builders. A passage tomb being symmetrically surrounded by monoliths is a characteristic feature of some Scottish monuments such as the stone circle at the south-west cairn, Balnuaran of Clava, Scotland (Lewis 1900, Figure 1, Somerville 1923, Figure 16) and at the nearby Leys passage tomb, also surrounded by a stone circle (Lewis 1900, Figure 3). Those examples feature noticeably more even spacing in pitch and gap distances.

At Newgrange, two tests were used to analyse pitch and gap distances. The first test examined the similarity in pitch between consecutive monoliths using nearest-neighbour distance analysis as developed by Neave and Selkirk (1983). The technique was also applied by the archaeoastronomer

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Prof. Clive Ruggles in his statistical study of 300 Scottish prehistoric monuments (Ruggles 1984, 228–243). To test the Newgrange data, the centroid of each monolith is regarded as being on or close to the circumference of the best-fit circle. The angular distance subtended at the centre of this circle by each monolith centroid and its nearest neighbour was measured and the resulting twelve angular distances summated. The test statistic t is this summation divided by the circle circumference, 360°. This can yield values ranging between 0 and 1 depending on the spread (clustering) in the data. The t statistic tests the hypothesis that the distribution of points (monoliths) on the best-fit circle is random against the alternative hypothesis that the distribution is clustered. The expected value of t under the random hypothesis is 0.5. A value close to 1 would indicate non-natural regularity (near perfect spacing) while a value close to zero would suggest strong evidence of clustering. For the Great Circle data, t = 0.56 and this indicates that the spatial arrangement of the monoliths is random, non-regular and marginally clustered. This is visually evident in the monoliths adjacent to the tomb entrance (see Figure 1).

For the second test, the arithmetic mean of the gaps measured orthogonally from each monolith inwards towards the kerb was found to be 11.8 m ±4.0 m with range 9.6 m to 14.1 m, 95% confidence. This strongly suggests that the monoliths were not positioned with a constant gap from the kerb as might be expected for visually appealing reasons, and as evident at some tomb and stone circle complexes. This conclusion justified alternative ideas to be explored including geometrical form and the degree of circularity.

Circular or elliptical shape?

The investigation of any ring of monoliths for indicative evidence of deliberate geometrical form, or morphology, is a two stage process. The quantitative stage helps determine the more likely, if any, construction model and defining parameters. Examples include the circle and the egg-shaped ellipse, a related curve form. The qualitative stage then tests the data for goodness-of-fit. Where the data accurately fit one or other model, this could suggest that the actual shape reflects a possible deliberate and culturally meaningful design idea or concept, intended, for example, to demarcate an enclosed formal space for assembly, ceremony or other unknown purpose.

For circle fitting, the least squares computational technique was used to determine the most probable centre and radius of the best-fit circle through the centroids of the twelve extant monoliths. The sample size has sufficient redundancy for statistical analysis (Table 1).

Let the general form of the equation of a circle be

$$x^2 + y^2 + 2gx + 2fy + c = 0. \quad [1]$$

The centre (x_0, y_0) is $(-g, -f)$ and the radius is

$$r_0 = \sqrt{(g^2 + f^2 - c)}\ . \quad [2]$$

The residual errors (v) between any monolith centroid (x_i, y_i) and the best-fit circle and best-fit ellipse are shown in Table 1, providing measures of the goodness-of-fit to each model. In the case of a circle, each residual error is

$$v_i = r_i - r_0, \quad [3]$$

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and $$r_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}\ . \quad [4]$$

The least squares solution also yields the precision of the circle centre from

$$\sigma_0^2 = \sigma_g^2 + \sigma_f^2, \text{ 95\% confidence.} \quad [5]$$

A similar approach determined the parameters and residuals of the best-fit ellipse using the general and translated form of the ellipse equation. Any comparison of the residuals in Table 1 is not meaningful because of the different degrees of freedom in the two models. Patrick and Wallace (1982) adopt an information theory approach as a possible method to overcome this problem. Either way, or because of the large range in the residuals in both cases, the conclusion is that the locations of the extant monoliths do not provide convincing evidence of a reliable fit to circular or elliptical form (Table 2).

TABLE 1. Residual errors of monoliths centroids to a best-fit circle and ellipse.

Monolith	v_{circle}	$v_{ellipse}$
GC17	+1.15 m	+0.95 m
GC13	-2.75 m	-1.75 m
GC11	-2.47 m	-2.00 m
GC9	+1.92 m	+1.80 m
GC7	+2.11 m	+1.35 m
GC5	+1.00 m	+0.02 m
GC3	-1.40 m	-1.70 m
GC1	-1.84 m	-1.20 m
GC−1	-0.74 m	+0.55 m
GC−2	+0.13 m	+1.70 m
GC−8	+0.59 m	+1.15 m
GC−10	+0.06 m	-1.00 m

TABLE 2. Summary statistics for circle and ellipse curve fitting.

	v_{circle}	$v_{ellipse}$
Standard deviation	±1.65 m	±1.44 m
Standard error	±0.48 m	±0.42 m
Range	±4.86 m	±3.80 m
Relative error	1:30	1:35

The task of setting out the Great Circle using a constant radius from the summit of an already extant cairn whose basal diameter and height are *c*. 85 m and 10 m–13 m respectively would have

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been an extremely difficult if not near impossible task given the likely basic technological skills (rope and peg) of the Bronze Age (and see Atkinson 1974, 1975). Additional curve-fitting analysis of the monoliths and kerbstones also found their mean centres to be 4.3 m apart, demonstrating the cairn and surrounding monoliths do not share a common geometrical centre. These findings, supported by O’Kelly (1982, 84), advocate that Great Circle as a term should not imply deliberate circular form and only used for description purposes.

Astronomical alignment and shadow casting

The burial chamber of Newgrange passage tomb receives direct light from the rising Sun for a period of several days centred on winter solstice. This has endured since the Neolithic. The observed shadow casting by GC1 onto K1 is an additional and recurring alignment phenomenon which has also endured since the Bronze Age with comparable seasonal timing and diurnal duration. This suggests that the period of winter solstice was important to users, not just in the Neolithic but in the time of the Beaker Culture. Based on this idea, might shadow casting by monoliths adjacent to GC1 hold seasonal significance at times other than winter solstice? The findings of the geometrical analysis add weight to this hypothesis and justified a broader investigation of astronomical alignments at the site.

Indicative astronomical declinations

The astronomical investigation first considered all possible alignments using the coordinates of the centre of K1 and each monolith centroid taken as line endpoints. The majority were rejected for lack of intervisibility caused by the blocking effect of the enormous cairn. Secondly, all pairs of monoliths only were considered *i.e*. with K1 excluded. The majority of those were rejected on similar grounds or because some of the monoliths have very low height. Pragmatically, this left twenty-eight possible alignments for testing purposes. Their indicative declinations were calculated from the latitude φ, azimuth A, and the altitude h of the local horizon. The method uses the azimuth by altitude solution of the celestial spherical triangle shown in Figure 3 (after Bomford 1980, 257–258) as

$$\cos A = (\sin \delta - \sin \varphi \sin h) / \cos \varphi \cos h. \quad [6]$$

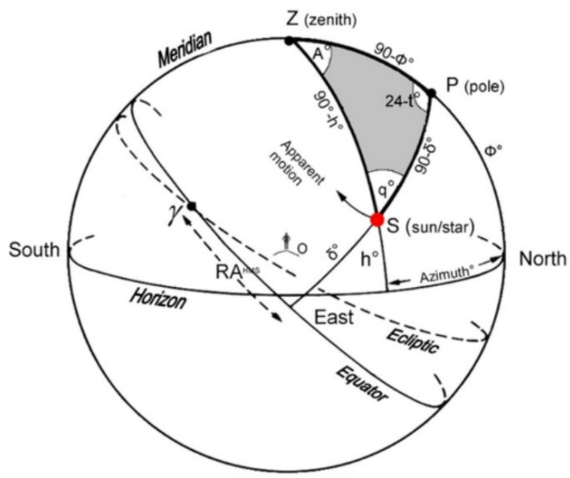

Fig. 3. Celestial sphere and astronomical triangle PZS (Bomford 1980, Fig. 4.1 with additions).

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Six of the twenty-eight alignments were within *c*. 1° of astronomically interesting declinations δ as shown in Table 3 and Figure 4. This criterion is generally accepted as appropriate for accepting or rejecting any alignment having potential cultural significance for studies of horizon-based astronomy likely/possibly practised in Neolithic and later prehistoric times.

TABLE 3. Preliminary astronomical declinations from alignment coordinates.

Alignment	Declination	Remarks
K1→GC1	-24° 54′	Winter solstice
K1→GC−1	-11° 21′	Mid-declination South
K1→GC−2	+00° 30′	Between winter and summer solstice (equinox)
GC5→GC3	+11° 33′	Mid-declination North
GC1→GC−2	+23° 15′	Summer solstice
GC11→GC7	-23° 49′	Winter solstice

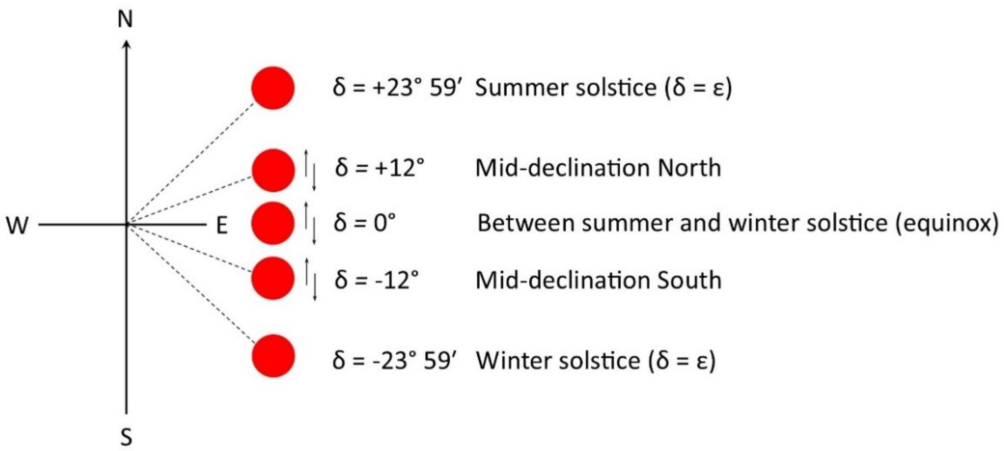


Fig. 4. Limiting and intermediate solar declinations of interest for *c*. 2500 BC when the Great Circle was constructed.

The declinations in Table 3 identify periods of the year when sunrise shadow casting by GC1, GC−1 and GC−2 will interact with kerbstone K1. The table also shows additional cases of inter-monolith shadow casting with potential calendrical significance *i.e.* GC5 to GC3, GC1 to GC−2 and GC11 to GC7. This justified a fuller investigation of shadow casting centred on these dates using computer simulation to first generate and then test a range of user-defined visualisations of the phenomena. Importantly, such an approach would accurately indicate when to visit the site to obtain crucial photographic evidence to verify the simulations.

AutoCAD simulation of shadow casting

The first analysis considered solar shadow casting by GC1 onto the vertical face of K1 at winter solstice. If shown in section, the shadow zone is formed below the tangent joining the apparent lower limb of the Sun, the apex of the gnomon and the surface of K1 (see Figure 2). The phenomenon was simulated in AutoCAD, initially to test the feasibility of the method for winter solstice in the current epoch when δ and ε are 23° 26′ and the phenomenon was witnessed. For viewing the digital model, azimuths (A) spanning the first half-hour after sunrise were calculated at five-minute intervals using the hour angle solution of the celestial spherical triangle (see Figure 3), t being the local hour angle[5] in

$$\tan A = \frac{\sin t}{\tan \delta \cos \varphi - \sin \varphi \cos t}. \quad [7]$$

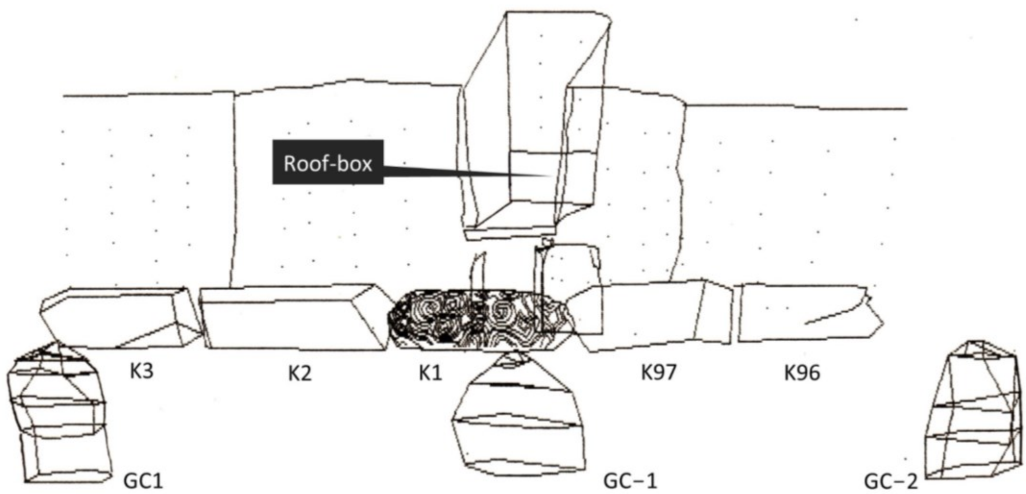
The corresponding apparent altitude of the lower limb of the Sun for each azimuth was then calculated in equation [6], corrected for low-angle atmospheric refraction[6] and the semi-diameter of the solar disc in

$$h' = h + r - SD, \quad [8]$$

where h′ = apparent altitude, h = true altitude, r = refraction and SD = semi-diameter of the Sun.

Each pairing of azimuth and altitude of the Sun was reversed, providing user input coordinates for viewing the digital model in AutoCAD. This approach adopts the Sun's view of the model, effectively projecting the outline of GC1, or any other monolith, onto the face of K1. Usefully, AutoCAD has two projection viewing modes termed parallel and perspective. The former was chosen to emulate the parallel nature of sunlight and create more realistic scenes replicating the true observed phenomena.

Simulations of GC1 projected onto K1 on winter solstice in the current epoch at five-minute intervals were verified against previously recorded photography of the true phenomenon (see Figures 5 and 6). This comparison validated the orientation and scale accuracies of the digital model and method. Shadow casting simulations for GC-1 to K1 and GC-2 to K1 were next simulated for dates indicated by the declinations in Table 3. Figure 5a illustrates one such scene when the projection of GC-1 reaches ground level at K1 following its passage, or track, diagonally down across the three-spiral motif. The declination of the Sun is then *c*. -12° corresponding to dates in mid-February and late October (see Table 4).



(a) Shadow casting for 17–18 February and 24–25 October, δ = *c*. -11° 40′.

Fig. 5. Simulated seasonal shadow casting at Newgrange.

[5] For a general treatment of field astronomy see The War Office (1958).

[6] The algorithm by P. Duffet-Smith (1990, 88) estimated low angle atmospheric refraction.

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Sunrise shadow casting from GC3 to GC5, additionally identified in Table 3 as an alignment with potential calendrical significance, was also digitally simulated. These tests agreed with subsequently acquired site photography of the phenomenon (see Figure 5e and Figure 9). The declination for alignment GC−2 to GC1, initially considered a summer solstice alignment, is now deemed fortuitous as both monoliths are not consecutive in the Great Circle. The alignment GC11 to GC7, also astronomically interesting, is discounted for the same reason.

Results

Shadow casting is simulated for three epochs of interest:

- 2500 BC (ε = 23° 59′) around when the Great Circle was constructed;
- 3200 BC (ε = 24° 02′) because O'Kelly had argued the Great Circle and passage tomb were contemporaneous;
- current epoch (ε = 23° 26′) to allow for comparisons between computer generated simulations and recorded photography of the phenomena.

In the Bronze Age the rising Sun at winter solstice was 1° 06′ further south than at present, the equivalent of 2.1 solar diameters. In the Neolithic, it was 1° 12′ further south than at present, the equivalent of 2.3 solar diameters. These azimuthal differences respectively subtend 0.3 m and 0.4 m over the 17 m gap separating GC1 from K1. Relatedly, GC1's shadow on winter solstice would have aligned slightly eastwards on the three-spiral motif by these small but discernible amounts in comparison to its present track. The computer simulations for each of the three epochs examined give the following results.

Shadow casting—simulated for Early Bronze Age

Figure 5 illustrates the simulations of shadow casting in the Bronze Age.

- At δ = –23° 59′, winter solstice, the shadow of GC1 would have tracked through the left side of the three-spiral motif on K1, being shifted 0.3 m to the right of its path in the present epoch (Figure 5b). The simulations accurately replicate the phenomena as seen in the Bronze Age. The diurnal change in δ is only 0° 01′ at this time of year linked to a diurnal azimuth change of 0° 02′ in sunrise. This is unnoticeable to the naked eye over several days, hence the perception of solar standstill on the horizon lasting for several days.
- At δ ≈ –12°, midway in declination between winter solstice and δ ≈ 0°, the shadow of GC−1 tracks through the middle of the three-spiral motif on K1 (Figure 5a and 5c). The diurnal change in δ is 0° 21′ at this time of year, linked to a diurnal azimuth change of 0° 36′ in sunrise, about one solar diameter.
- At δ ≈ 0°, midway between winter and summer solstice (see footnote 7), the shadow of GC−2 tracks through the middle of the three-spiral motif on K1 (Figure 5d). The diurnal change in δ is 0° 24′ at this time of year, linked to a noticeable diurnal azimuth change in sunrise of 0° 40′, or 1.25 solar diameters.
- At δ ≈ +12°, midway in declination between δ ≈ 0° and δ ≈ +23° 59′ (summer solstice), the shadow cast by GC3 aligns with GC5. The simulation in Figure 5e (left) shows the alignment in reverse *i.e.* looking towards the Sun with GC5 in the foreground. This is photographically illustrated in Figure 5e (right).

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Shadow casting—simulated for the Neolithic

The second stage of the analysis examined shadow casting in the Neolithic in *c*. 3200 BC when the Great Circle was argued as being contemporary with, or even predating, the passage tomb (O'Kelly 1982, 82). If so, the shadow cast by GC1 to K1 would have then tracked 0.4 m to the right of its present path at winter solstice. However, a Neolithic date of construction for the Great Circle is now discounted by archaeologists. That data, although investigated, are not shown here for that reason.

Shadow casting—simulated for the current epoch

Digital simulation of shadow casting in the current epoch provided timed visualisations of the phenomena for comparison with site photography recorded between 1986 and 1989. The results are shown in Figures 6–9.

- At $\delta = -23° 26'$, winter solstice, the simulated shadow of GC1 tracks tangentially beneath the three-spiral motif on K1 as verified by site photography (Figure 6).
- At $\delta \approx -12°$, midway between winter solstice and equinoxes, the simulated shadow of GC−1 tracks through the middle of the three-spiral motif on K1 as verified by site photography (Figures 7).
- At $\delta \approx 0°$, midway between the winter and summer solstice[7], the simulated shadow of GC−2 tracks through the centre of the three-spiral motif on K1 as verified by site photography (Figures 8).
- At $\delta \approx +12°$, midway between the equinoxes and summer solstice, the shadow of monolith GC3 aligns with GC5 as verified by site photography (Figures 9).

A summary of the indicative astronomical declination limits and their corresponding dates in the Gregorian calendar is given in Table 4. These data will facilitate modern viewing of the phenomena, each observable over a period of several days provided cloud-free conditions prevail. The phenomena are predictable and recur biannually with the exception of shadow alignment GC1 to K1. This is a singular and unique alignment event which can only occur at winter solstice when the rising Sun is at its most extreme azimuthal limit on the south-eastern horizon.

[7] The eastern and western horizons at Newgrange have angular altitudes of *c*. +0°.5 and +0°.3 respectively. The diurnal change in the azimuth of sunrise and sunset in late March and September is 00° 40', the equivalent of 1.25 solar diameters regardless of the epoch. A simple empirical method for determining the particular day when the Sun noticeably rises and sets in diametrically opposite directions (the equinox to us), given a near-level east and west horizons such as at Newgrange, is to use two poles/sticks set vertically into the ground. If these have an exact east-west alignment, the reciprocal of any naked-eye sighting on the disc of the rising Sun on that day would intersect the disc of the setting Sun. If three poles were used, these would be co-linear with the Sun on that day but angled on any other day. Either method would thus mark the mid-point between the Sun's azimuthal limit on the southeast horizon at winter solstice and the northeast horizon at summer solstice. If two poles were aligned on the rising Sun one day either side of this day, the reciprocal sighting would miss hitting the disc of the setting Sun by 2–3 solar diameters. If two days either side of this date, the sighting error would be 5–6 solar discs. If three days either side of this date, the sighting error would be 7–8 solar discs. This simple method thus has a potential accuracy of better than three days for determining the mid-position of the Sun in its annual apparent journey along the horizon. Whether such a technique was ever used for this purpose in the prehistoric past is unknowable.

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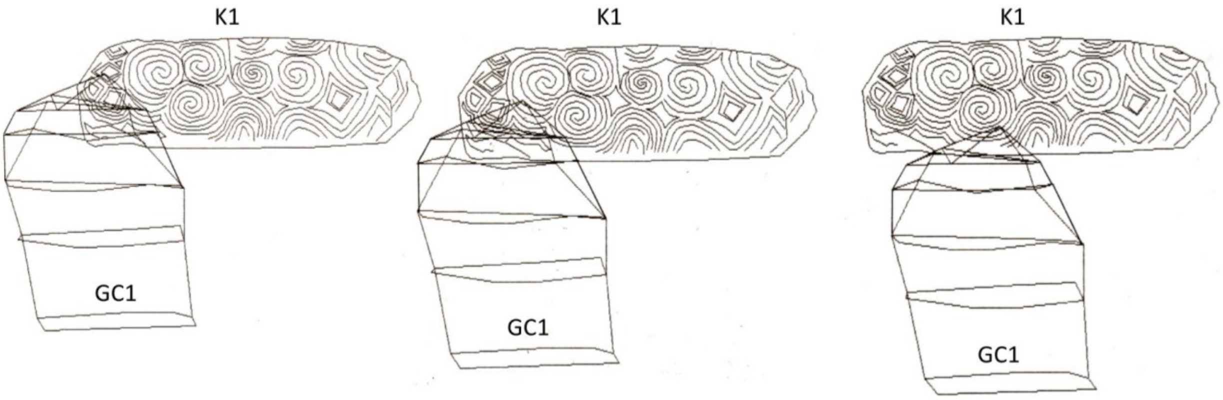
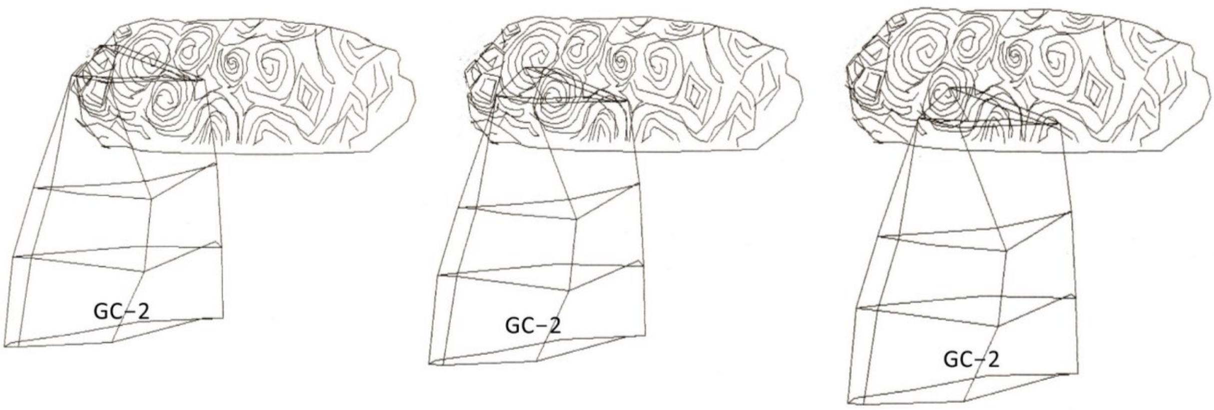


(b) GC1 projected onto K1, δ = –23° 56′ for winter solstice *c.* 2500 BC.

(c) GC−1 projected onto K1, δ = –12° for *c*. 2500 BC.



(d) GC−2 projected onto K1, δ = 0° for *c*. 2500 BC.

Fig. 5 (continued). Simulated seasonal shadow casting at Newgrange.

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(e) Left: Simulation of alignment GC5–GC3 for δ ≈ +12°.
Right: General view from GC5 to GC3 looking east-north-east. The height of GC5 is *c*. 0.5 m (1 m scale). Respectively, GC1, GC−1 and GC−2 are visible in the distance (photo. F Prendergast).

Fig. 5 (continued). Simulated seasonal shadow casting at Newgrange.

TABLE 4. Declination limits of shadow casting on the three-spiral motif on K1, and on GC5.

Alignment	Declination limits	Duration	Season	Date range
GC1→K1	–23° 26′ and –23° 59′	12 days (half-period)	Winter solstice	In the Bronze Age, shadow ingress on the three-spiral began *c*. 12 days before solstice (see Figure 10a).
GC−1→K1	–09° 51′ and –12° 53′	10 days	Mid-declination South/−	15–24 February 18–27 October
GC−2→K1	–01° 14′ and +01° 30′	8 days	Around equinox	17–24 March 19–26 September
GC3→GC5	+11° 17′ and +12° 58′	6 days	Mid-declination North/+	19–24 April 18–23 August

Photographic Verification

Shadow casting phenomena at Newgrange was first photographed by the author on winter solstice sunrise, 1986 December 20. This was followed by a systematic campaign of recording in 1987–1989. Figures 6–9 show the photographic evidence, verifying the temporal changes in shadow casting predicted by the computer simulation in Table 4. Each image is dated, time stamped and tagged with values of solar declination, azimuth and altitude. The necessity for clear skies and visible sunrise accounts for the extended period of time to acquire the imagery. Relatedly, Ireland’s climate in the prehistoric past, and whether skies were more cloud-free at that time, is briefly considered in the Discussion section.

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1990 December 19
UTC 09:00
δ = −23° 25′
Sun azimuth = 134° 50′
Sun altitude = +01° 43

(a) Shadow is first visible on the left edge of K1 shortly after sunrise.

1990 December 19
UTC 09:10
δ = −23° 25′
Sun azimuth = 136° 53′
Sun altitude = +2° 41′

(b) Shadow in the current epoch passes underneath the three-spiral motif. During the Bronze Age, the shadow tracked through the motif (see Figure 5b).

1990 December 19
UTC 09:25
δ = −23° 25′
Sun azimuth = 140° 00′
Sun altitude = +04° 05′

(c) Shadow egress from the face of K1, reaching ground level under the central vertical groove at the top of kerbstone.

Fig. 6. Annual shadow casting for GC1→K1, valid for δ = −23° 26′, winter solstice.

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1989 February 20
07:48 UTC
δ = −10° 53′
Sun azimuth = 110° 15′
Sun altitude = +01° 28′

(a) Shadow is first visible on the left edge of the three-spiral motif. During the Bronze Age the shadow would have been a few centimetres to the right.

1989 February 20
07:57 UTC
δ = −10° 53′
Sun azimuth = 112° 04′
Sun altitude = +02° 38′

(b) Shadow nears the lower edge of the three-spiral.

1989 February 20
08:04 UTC
δ = −10° 53′
Sun azimuth = 113° 30′
Sun altitude = +03° 32′

(c) Shadow is at the base of kerb stone K1. On the left side, GC1's shadow touches kerbstones K3/K4.

Fig. 7. Biannual shadow casting for GC−1→K1, valid for δ ≈ −12°, mid-declination South.

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1989 March 17
06:48 UTC
δ = −01° 20′
Sun azimuth = 93° 39′
Sun altitude = +01° 23′

(a) Shadow begins ingress on the three-spiral motif three days before δ = 0°. Egress will occur eight days later. The shadow moves across the face of K1 by a most noticeable 0.3 m per day.

1987 September 22
06:33 UTC
δ = +00° 30′
Sun azimuth = 92° 39′
Sun altitude = +02° 49′

(b) Shadow hits the three-spiral motif on K1. Simultaneously, shadows cast by GC−1 and GC1, seen on the left, align on kerb stones K4 and K8 respectively. Kerbstone K8 has a dot-in-circle motif picked on the top surface.

1989 March 23
06:49 UTC
δ = +01° 02′
Sun azimuth = 92° 36′
Sun altitude = +03° 25′

(c) Shadow egresses the face of K1. For this scene, the access stairs and barrier were temporarily removed to facilitate photography.

Fig. 8. Biannual shadow casting for GC−2→K1, valid for δ ≈ 0°, around the equinoxes.

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1989 April 15
05:31 UTC
δ = +09° 46′
Sun azimuth = 73° 06′
Sun altitude = +00° 19′

(a) From GC5, the Sun rises 3° 40′ to the right of alignment GC5 to GC3. This event occurs 6 days before when δ = +12°. Monoliths GC1, GC−1 and GC−2 are visible to the left. This image, along with (b) and (c) below, reveals how any alignment can be simply used to track and predict time by diurnally observing the Sun on the horizon.

*2019 August 24**
05:26 UTC
δ = +11° 12′
Sun azimuth = 71° 47′
Sun altitude = +01° 03′

(b) Sunrise on alignment GC5 to GC3 recorded on a site visit in 2019*.

**This is a supplementary image post-dating original fieldwork.*

1989 August 21
05:30 UTC
δ = +12° 07′
Sun azimuth = 71° 07′
Sun altitude = +01° 39′

(c) Furthest left, the shadow cast by GC3 is aligned on GC5. Sunrise shadows cast by GC1, GC−1 and GC−2 are visible on the right. This scene vividly demonstrates the dramatic shift in shadow direction related to changes in seasonal time.

Fig. 9. Biannual shadow casting, with emphasis on GC3→GC5 in far-left of image, valid for δ ≈ +12°, mid-declination North.

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Digital relocation of the monoliths

This test leveraged the power of the digital method where each monolith in the AutoCAD model is given an alternative location. The changes in simulated shadow casting can then be compared to the true/observed phenomena in Figures 6–9 for the current epoch, or any other epoch such as the Bronze Age. Monoliths were first re-positioned laterally along the locus of the best-fit circle. These simulations provide a range of experimental outcomes:

- GC1 to K1
  - if GC1 is moved south-west along the locus of the best-fit circle by half a diameter of its base from its present location, the shadow cannot touch the three-spiral motif on K1;
  - if GC1 is similarly moved north-east along the locus of the best-fit circle by one diameter, the shadow cannot touch the three-spiral motif on K1.
- GC−1 to K1
  - if GC−1 is moved south-west along the locus of the best-fit circle by half a diameter, the shadow cannot touch the three spiral motif on K1;
  - if GC−1 is moved north-east along the locus of the best-fit circle by half a diameter, the shadow cannot touch the three-spiral motif on K1.
- GC−2 to K1
  - if GC−2 is moved south-west along the locus of the best-fit circle by half a diameter, the shadow cannot touch the three-spiral motif on K1;
  - if GC−2 is moved north-east along the locus of the best-fit circle by half a diameter, the shadow cannot touch the three-spiral motif on K1.

Next, each monolith was moved radially nearer to/further from the passage tomb kerb.

- GC1, GC−1, GC−2
  - if moved radially further from K1 by one diameter of the base, the shadows cannot touch the three-spiral motif on K1;
  - if moved radially nearer to K1 by one diameter, the shadows touch the three-spiral motif on K1.
- GC3, GC5
  - if GC3 or GC5 is moved radially nearer or further from the kerb by more than one diameter, the shadow of GC3 will not align with GC5 at sunrise on the indicative dates in Table 4.

These tests demonstrate how monolith locations are critical, in terms of goodness of fit to the calendrical hypothesis, to about one diameter of their basal locations. This also applies if re-location is radially away from the kerb or laterally along the locus of the Great Circle in either direction.

Declination limits of shadow casting

The declination limits for seasonal shadow casting by GC1, GC-1 and GC-2 draw attention to the three-spiral motif on K1. While O’Kelly contended that K52 rivalled K1 ‘in the quality of its design and the excellence of its technique’ (O'Kelly 1982, 158), the author considers the three-spiral motif to be the most accomplished and impressive compound symbol, not just on K1 but in the entire repertoire of megalithic art found at Newgrange (see O'Kelly 1973, O'Kelly 1982, 152–185). Interestingly, the three-spiral motif is incised on the left-hand side of the central vertical groove on that kerbstone but any

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explanation for this preferential sidedness cannot be given. What is certain is that the decoration on K1 was applied after the stone was placed *in situ* into the kerb since the megalithic art terminates horizontally at ground level (see Figure 10).

Figure 10 shows the declination limits of shadow casting by GC1, GC−1 and GC2 at ingress and egress mapped onto the three-spiral motif on K1. These coincide with three temporal divisions of the solar year in the Bronze Age: winter solstice at δ = −23° 59′, mid-declination South at δ ≈ −12°, and δ ≈ 0° (around equinox). The angular inclination of each shadow path on K1, as depicted by the dotted arrow lines in Figure 10, additionally mirrors the inclination path of the climbing Sun.[8] The spacing between the declination lines on K1 further indicates the diurnal intervals (date range) for shadow casting in each season. Arguably, this highlights how the three-spiral motif on K1 is focal.

In more detail, Figure 10a shows the declination limits for solar shadow casting by GC1 onto the three-spiral motif on K1 at winter solstice in the Bronze Age (*cf*. Figure 6). The half-period from ingress to egress is about twelve days. Shadow casting by GC1 on the three-spiral motif would have occurred in the Bronze Age when the Sun's declination was between the limits −23° 26′ and −23° 59′ corresponding to an azimuth range at sunrise[9] of 131° 40′ and 132° 51′. Winter solstice could have been easily determined to an accuracy of a few days by watching the shadow's progression towards K1 each dawn. In the current epoch, the shadow can now only reach the lower declination line and limit, tangentially below the motif (see also Table 4 and Figure 6).

Figure 10b shows the limits for shadow casting by GC−1 to K1 when the Sun's declination is about midway south in value between winter solstice and the equinoxes. In contrast to GC1's shadow on K1 at winter solstice, the shadow cast by GC−1 now tracks across the face of K1 on two seasonally different periods. The period from ingress to egress on the three-spiral motif is about ten days, the first seasonal occurrence after winter solstice being on 15–24 February. The phenomenon repeats with the return of the Sun to the same position on the horizon the following 18–27 October. This shadow interaction by GC-1 with the three-spiral motif will only occur if the Suns' declination is between the limits −09° 51′ and −12° 53′ corresponding to an azimuth range at sunrise of *c*. 106° 30′–111° 30′ (see also Table 4, Figure 5a and Figure 7).

Figure 10c shows the limits for shadow casting by GC−2 to K1 when the Sun's declination is midway between winter and summer solstice, centred on δ ≈ 0° or equinox. The period for ingress to egress on the three-spiral motif is about eight days, with first seasonal occurrence being on 17–24 March. The phenomenon repeats with the return of the Sun to the same position on the horizon on the following 19–26 September. Shadow interaction by GC−2 with the three-spiral motif will only occur if the Sun's declination is between the limits −01° 14′ and +01° 30′ corresponding to an azimuth range at sunrise of *c*. 91° 30′–87° 30′ (see also Table 4 and Figure 8).

Figure 9 illustrates the limits for shadow casting by GC3 onto GC5 when the Sun is at mid-declination North, or midway between δ ≈ 0° and summer solstice (ε = 23° 59′ in the Bronze Age). The period from ingress to egress on GC5 is about six days with first seasonal occurrence after winter solstice being on 19–24 April. The phenomenon repeats with the seasonal return of the Sun to the same apparent position on the horizon on the following 18–23 August. Shadow interaction by GC3 onto GC5 will only occur if the Sun's declination is between the limits +11° 17′ and +12° 58′ corresponding to an azimuth range at sunrise of *c*. 67° 30′–70° 30′ (see Table 4).

[8] The inclination angle α of the Sun's path with the horizon is given by the spherical cosine rule solution of the celestial astronomical triangle PZS and $\sin\alpha = \cos\varphi \sin A / \cos\delta$ (see Figure 3). The inclination angle of the shadow paths on K1 in Figure 10 are 28°.4 at winter solstice, 34°.6 at mid-declination south and 36°.3 at the equinoxes.

[9] Quoted azimuths are for when the lower limb of the Sun is on the apparent local horizon having an altitude of 0° 00′–0° 30′.

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(a) GC1 shadow path on K1 for *c*. 2500 BC showing the declination of the turning point at winter solstice, δ = –23° 59′, and ingress and egress declinations on the three-spiral motif at δ = −23° 26′.

(b) GC−1 shadow path on K1 for *c*. 2500 BC showing the declination limits at ingress and egress on the three-spiral motif.

(c) GC−2 shadow path on K1 for *c*. 2500 BC showing the declination limits at ingress and egress on the three-spiral motif centred around δ ≈ 0°.

Fig. 10. Declination limits (approximate) for shadow casting mapped onto entrance kerbstone K1 (after Prendergast 1991, Figure 6.19 with additions). Photo: F Prendergast ©1986.

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Overall, the evidence for shadow casting indicative of an alignment on summer solstice sunrise is considered weak. While GC−2 to GC1 has such an astronomically interesting declination, this is now considered fortuitous, both stones being non-consecutive in the Great Circle.

Statistical Analysis

This research is founded on spatial data collected and processed by precise field survey techniques and photogrammetry. The data are used to analyse circle fitting, compute astronomical declinations and simulate shadow casting verified by field photography. However, such approaches do not provide any statistical backing to the solar calendar hypothesis or quantify the probability that the Great Circle monoliths were intentionally erected for shadow casting purposes.

The study of prehistoric stone circle sites in England and Scotland by the British engineer Prof. Alexander Thom is one example of how statistical methods are used to assess*, inter alia*, the possibility that axial alignments and associated outliers may have had astronomical significance (Thom 1955). The astronomer Prof. Gerald Hawkins’ theories on the alignments at Stonehenge, England, are another example (Hawkins 1966). A review of Hawkins’ work by the British prehistorian R. J. C. Atkinson is critical of Hawkins’ findings, writing: ‘….in any investigation of this kind it is essential to test whether the results differ significantly from what would be expected if chance alone were operating. His result here is wrong all through. The probability is wrong; the method of testing the hypothesis is wrong; and the restriction of the possible sight-lines to 50 is wholly inadmissible.’ (Atkinson 1966, 214). In a recent statistical study of three-hundred prehistoric free-standing megaliths in Western Scotland, Ruggles brought advances in archaeoastronomical techniques to bear on his data obtained at those sites (Ruggles 1984). That research highlights how astronomy is linked to the development of human conceptualisation of space and time and draws attention to the ambiguities and dangers inherent in using statistically flawed methods and deriving wrong inferences.

In the analysis here, the null-hypothesis is that the shadow casting events observed at Newgrange are random and due to chance. For data testing purposes, certain assumptions and constraints are necessarily made with caution. The first assumption is that any two alignment events are independent *i.e.* the probability that either event happens is not affected when the other event happens or fails to happen. Secondly, significant sunrise targets, expressed as azimuths derived from astronomical declinations, are randomly distributed over half of the horizon *i.e.* only sunrises are considered as targets in the eastern half of the horizon. Thirdly, the rising Sun at solstice is a standstill target and considered a singular event (see Figure 4). For statistical testing purposes, the remaining solar targets of interest are treated as two events, the Sun appearing to travel on the horizon in opposite directions in different seasons. This seems valid since sunrise on the vernal and autumnal equinoxes, for example, are considered as two separate calendrical events even though they occupy the same azimuth. Mindful of the statistical dangers of a Type I or Type II error, different probability scenarios are considered (see Table 5).

Bernoulli’s Law is used to calculate the probability that a specified number of alignments will hit exactly r significant sunrise azimuths in n attempts (see Blakey 1965, 465–468, Atkinson 1975, Heggie 1981, 242–32, Schaefer 1986). The overall probability P that at least *r* targets are hit in *n* attempts for the same number of alignments is

$$P = 1 - \sum_{s=0}^{r-1} \frac{n!\, p^s (1-p)^{n-s}}{s!\,(n-s)!}\,, \qquad [9]$$

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where $s = 0, 1, ,2 \ldots\ldots (r-1)$, *p* is the proportion of the horizon occupied by all astronomical targets, and *P* is the overall probability that the observed number of targets is due to chance alone.

For calculating *p*, the azimuth ranges for observed shadow ingress and egress on the three-spiral motif on K1 are determined from the declination ranges shown in Figures 10a–10c. In Figure 10a the range is 1° 13′ at winter solstice, in Figure 10b is 4° 54′ at $\delta \approx -12°$ and in Figure 10c is 4° 34′ at $\delta \approx 0°$. In Figure 5e, the azimuth range for GC3's shadow hitting GC5 is 2° 23′ at $\delta \approx +12°$. These summate to 13° 04′, the total width of the horizon sectors in which the astronomical events indicated in Figure 4 happen. The probability *p*, taking the eastern half of the horizon only, is 13.07/180, or 0.073. If the arc of the horizon is narrowed to 87°, this being the angular width of the solar-arc from sunrise on winter solstice to sunrise on summer solstice at Newgrange, *p* is 0.15. Patrick (1974b) and Ray (1989) similarly used maximum azimuthal limits to discuss the likelihood of winter solstitial alignment at Newgrange passage tomb being intentional but did not report associated probability values. Heggie (1981, 213) did so for Patrick's azimuthal range of 4° 42′ for the roof-box. By including both winter and summer solstice sunrises as targets, Heggie found that to be .07 and: 'not really significant enough to excite much interest'. Interestingly, if Ray's azimuthal range of 3° 40′ is given similar treatment, the probability improves to .04. If Neolithic people were more concerned with an astronomically meaningful sector rather than any precise direction or a horizon feature, the near dismissal of Patrick's findings by Heggie could be judged as excessively rigorous in that context.

Turning now to shadow casting at Newgrange during the Bronze Age, Bernoulli's Law tests the null-hypothesis that the observed phenomena occur by chance. The probability *P* for different values of the parameter *p* is shown in Table 5. A value for $P \leq .05$ would suggest that the alignments cannot be explained by chance and the greater is the likelihood of intentionality.

TABLE 5. Probability of solar shadow casting alignments at Newgrange

Row no.	*p*	*r*	*n*	*P*	Remarks
1	.07	7	28	.001	180° horizon (eastern); reject the null-hypothesis
2	.15	7	28	.05	87° horizon (solar arc); do not reject the null-hypothesis

In row 1 of Table 5, s must be ≥ 5 for $P < .05$ and in Row 2, s must be ≥ 8 for $P < .05$. Furthermore, if an eight-fold division of the solar year is argued by the inclusion of an alignment on summer solstice the null hypothesis is also rejected because P < 0.001 for p values of 0.07–0.15. Providing the parameters p, r and n are validly chosen, one conclusion is that the location of monoliths GC1, GC-1, GC-2, GC3 and GC5 were deliberately placed for solar shadow casting in astronomically interesting seasons. Intentional shadow casting cannot be inferred if the horizon is constrained to the angular width of the eastern solar arc of 87°. The locations of the remaining monoliths surrounding the passage tomb cannot be fully explained.

Discussion

The only published archaeological mention known to the author of solar shadow casting at a British or Irish prehistoric monument is by the antiquarian George Bain. Specific mention of such phenomena is found in his description of the Bronze Age burial cairns at Balnuaran of Clava, Scotland. The middle of three structures there is a ring cairn flanked to the north-east and south-west by two passage tombs, each surrounded by eleven upright monoliths. Bain, referencing plans of the Clava monuments by the surveyor James Fraser, wrote: ‘it must have been necessary for the men who set these huge stones to have watched and noted sun's shadow most carefully ere they could have determined their position’, and : ‘in placing these large stones to the south, the builders did so with some reference to the sun's course.’ (Bain 1886–7, 127). The following, in the same paper, is also noteworthy because of its time:

> All who are acquainted with even the elements of astronomy will perceive at once the importance of these points. They are precisely the facts which could, by mere observation of the sun's shadow alone, be observed and recorded, and it is, I think, beyond belief that these stones could have been set up in that order by mere accident, giving us, as they do, noon time, the solstices and the equinoxes.

(ibid.1886–7, 130).

Necessarily broadening the search to beyond Britain and Ireland, the American anthropologist Elizabeth Chesley Baity described how: ‘The gnomon, which was virtually universal among the ancient cultures, could have been independently invented as a result of observations of shadow-casting by natural objects. All peoples with fixed dwellings must have observed that the midwinter and mid-summer sunrises reached certain distant markers on the horizon and then changed directions.’ (Baity 1973, 442). Relatedly, the psychologist Carl Jung considered the universal relationship between human instinct and archetypes and how these manifested themselves, often in created symbolic images and built structures. He wrote: ‘They are without known origin: and they reproduce themselves in any time or in any part of the world—even where transmission by direct descent or “cross fertilization” through migration must be ruled out.’ (Jung 1964, 58). One cultural site in North America, investigated by archaeoastronomical methods, provides backing for Jung’s ideas. The phenomena, although relating to a very distant culture, location and time, exhibit a striking degree of similarity with the shadow casting at Newgrange.

The Anasazi Indians who lived in Chaco Canyon in north-western New Mexico in AD 400–1300 constructed multi-storey pueblos, large ceremonial centres, and had a highly developed system of roads, irrigation, communication and trade (Lister and Lister 1981). Their accurate lunar-solar calendar system could determine the times of solstices ($\delta = +23°\ 34'$ in AD 1000) and equinoxes ($\delta \approx 0°$) for agricultural and ceremonial purposes. One discovered example of their calendrical knowledge is a non-natural vertical assembly of stone slabs narrowly spaced apart to create slits. These collimate light from the Sun and the Moon (as distinct from the solar-cast shadows at Newgrange) onto a vertical rock panel immediately behind the slabs. This is decorated with two incised spiral petroglyphs onto which a distinctive solar light pattern moves downwards through the larger of the two spirals only at astronomically key times of the year (Sofaer, Zinser, and Sinclair 1979). Figure 11 illustrates the light beam’s progression across the larger spiral. That case study demonstrates not just an attested functional and symbolic link between the cyclical movement of the Sun and the spiral motif but the ubiquity of such symbols amongst unconnected cultures as earlier described by Jung.

Turning back to Newgrange, the method for digitally replicating solar shadow casting is robust. Astronomical computations of azimuths and altitudes use computer programs by the author, drawing on published positions of the Sun (HM Nautical Almanac Office 1987–1990). The simulated phenomena in Figure 5 are photographically verified in Figures 6–9. Figure 6 shows the phenomenon on winter solstice, the period of the year widely regarded as culturally prime in a ceremonial and ritual sense. It is a time characterised by the transition from decreasing to increasing daylight length. This is associated with a gradual but more noticeable decrease in the azimuth of sunrise after the so-called turning/reversal point is reached on the south-eastern horizon. The solstice is therefore discernible and determinable by naked-eye methods, certainly to within a few days. Experimentally, the author has used a distant distinctive natural feature on the horizon close to the Sun's turning point to observe the shift in successive sunrise positions preceding and following a solstice. When the Sun returns to the same memorised reference point, the solstice is easily deduced to within a day or two by halving the elapsed days. In the Bronze Age a simple tally system could have been used to record the number of such elapsed days. The effect of parallax is reduced if a distant horizon is chosen.

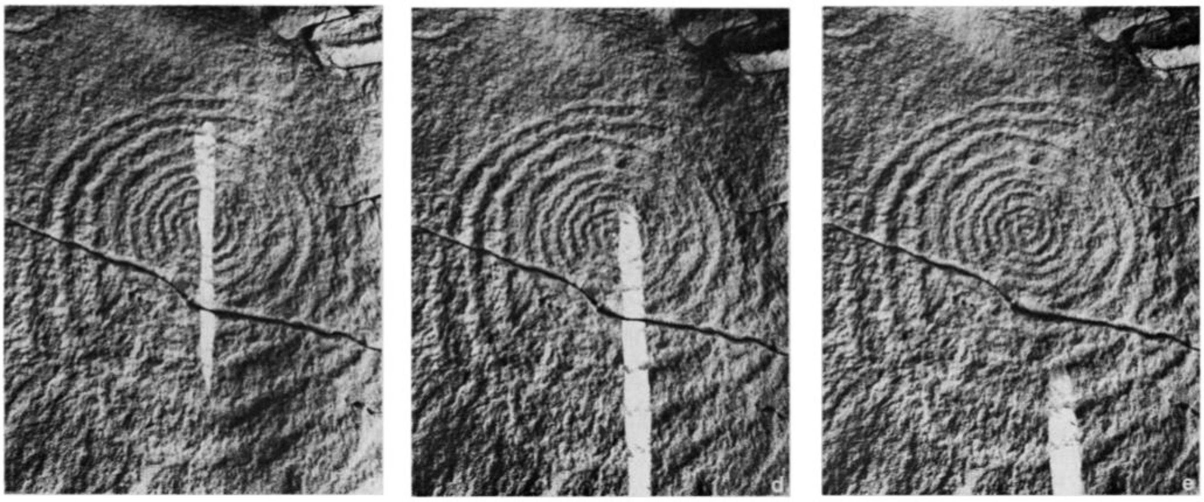

Fig. 11 Sunlight collimated onto the inscribed spiral petroglyph on summer solstice, Chaco Canyon. The phenomenon begins (ingress) as a light-spot outside the spiral, quickly lengthens into a 'light-dagger', and then descends downwards through the centre of the spiral to eventually exit (egress) eighteen minutes later (Soafer, Zinser and Sinclair 1979, Figure 7c–e; reproduced by kind permission of the authors).

The approximate time of winter solstice can still be predicted at Newgrange by naked-eye observance of the advance of GC1's shadow towards the three-spiral motif on K1 (see Figure 6). In the Bronze Age the shadow would have moved into the motif as revealed by computer simulation. Importantly, the now well-documented solstitial alignment of the Neolithic passage tomb provides evidence for such a sky watching tradition having existed in the Boyne Valley for at least five-hundred years before construction of the Great Circle. Interest in the apparent motion of the Sun on the horizon during the Neolithic is supported by Ruggles and Whittle (1981, 246–247) who wrote: 'The realisation that the roof-box over the entrance to Newgrange was perfectly aligned on midwinter sunrise seems confirmation that Neolithic people intentionally and intelligently constructed some ritual monuments to be in line with selected celestial events'. The question is then, was solar shadow casting as described here ever used for ritual or ceremonial purposes in the Bronze Age? If ever used in such a fashion, had it a calendrical role in an agrarian society preoccupied with crop planting, harvesting and the changing seasons? Speculating further, might shadow casting relate to continued special interest, even worship, of the three-spiral motif, symbolising the perpetual cycle of the Sun's journey on the horizon? If the Sun was perceived as the controller and giver of seasonal time, did the shadow casting phenomena mark seasonally important divisions of the year? Might any ritual engagement with shadow casting have been the preserve of an elite who took their authority from the celestial realm and the supreme source of power in the cosmos and sky–the Sun? These ideas and thoughts are partly predicated on visible sunrises being more the norm than occasional and introduces the need to briefly consider prevailing climate at the time when the Great Circle was in use.

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Bronze Age and paleoclimatology

Photographic verification of the computer-simulated phenomena required numerous site visits related to frequent obscureness of sunrise due to cloud. This raises the question - were skies more cloud-free in Bronze Age Ireland? O'Kelly (1976), drawing on G. F. Mitchell and H. M. Parkes (1948–50) used a system of time zones first proposed by Knut Jessen (1948–1950) for describing when plant pollen became trapped in mud deposits and lake beds in prehistoric times. Inferences on past climate, or paleoclimate, can be made from such data. Zone V in that system, which commenced about 7000 BC, is thought to have experienced a continental type climate which continued into Zone VII, the Atlantic period beginning about 5500 BC. Temperatures at that time are considered to have been about 2° C higher than at present, implying a greater prevalence of clearer skies at that time. Herity and Eogan (1989, 4) also adopted Jessen's nomenclature in describing Zone VIIb, a Sub-Boreal phase lasting 3000–1000 BC. This period spans the time of the Great Circle at Newgrange and is described by Herity and Eogan as being drier and warmer by as much as 2°.5 C compared with present. The British climatologist Hubert Lamb likewise noted that the most distinctive feature of the post-glacial era was the increasing warmth with average global temperatures in 5000–3000 BC being greater by 1°–3° C than today. Lamb, drawing on his climatological diagrams, additionally commented on the spread of megalithic monuments from the Mediterranean to Brittany and to as far north as Orkney as follows:

> The apparent construction of many of these stone circles as solar, or astronomical, observatories suggests—particularly in the case of the Hebrides and Orkney—that the skies were less frequently clouded over than they are today. This is a suggestion that is entirely consistent with the reconstruction of the prevailing wind circulation, with a more northern position of the anti-cyclones, accompanying the warm climate regime. The recent discovery that some of the megalithic tombs and circles at Carrowmore in Ireland are the earliest examples so far found anywhere, dating from between 4500 and 3700 BC (corrected radiocarbon dates) does not alter this picture. Whether or not they also had astronomical associations, reconstructions of the climatic patterns prevailing indicate already from well before those times regimes with frequent anticyclones and more frequently clear skies than now in this part of the world.
>
> (Lamb 1982, 127)

The archaeologist Seamus Caulfield also referenced paleoclimate following his discovery of the Neolithic stone-wall field systems in Co. Mayo, western Ireland. He wrote: 'The post-glacial climatic optimum reached over 2° C warmer than at present and around 3000 B.C. it is thought to have been 1°–2° C higher than at present.' (Caulfield 1981).

To be present outside Newgrange passage tomb at dawn when the rising Sun seems to animate the shadows cast by the Great Circle monoliths is a profound experience. Such a feeling is further augmented by the realisation of being witness to seemingly mysterious phenomena that have been shown here to be immutable since the Bronze Age. This leads to related questions on ancient concepts of temporality and how prehistoric architecture might have been used to capture or control time in a predictive sense.

Calendar models and prehistoric Ireland

The prehistoric solar calendar model in Table 6 is based on a division of the year determined by naked-eye observation of the apparent diurnal motion of the Sun on the horizon. The simplest is a four-fold-division of the year related to the directions of sunrise or sunset at winter solstice, summer solstice and an equal division between these limits (see Figure 4). Greater precision using a further four-fold division between those limits gives an eight-fold division of the solar year (Heggie 1981, 222–223, MacKie 1988, 211–213, McCluskey 1989). Other ancient systems are also known and historically verifiable, particularly Quarter Days.

The Irish Quarter Days, or Mid-Quarter Days, are a well-documented set of festivals days known to have once symmetrically divided the agricultural year (see Table 6). Their origins can be traced to the Early Medieval period, AD 400–900, onwards. The evidence is drawn from archaeology, folklore, history, legend and mythology (MacNeill 1962, Chaney 1964, Ó Danachair 1965, McCluskey 1989). Sometimes labelled Celtic Festivals, reflecting a similar calendrical tradition in Britain and Continental Europe, these were major events with possible roots in the Iron Age, *c*. 800 BC–AD 400. Four major festivals regulated the farming year and were marked by great gatherings and feasting at ritual centres located at places of high elevation throughout Ireland (MacNeill 1962 *op. cit*.); locations with height were apparently favoured for their vantage over the crops and farmland below. Notional festival dates, approximate astronomical declinations and their traditional names are listed in Table 6 for comparison with the proposed Newgrange shadow casting calendar model.[10]

Pushing further back in time, the earliest written European evidence for a prehistoric solar calendar and mid-quarter day festivals is found in the lunar-solar Calendar of Coligny. Discovered inscriptions on bronze tablets are interpreted as a record of the calendrical practices by the Celts of Roman Gaul and thought to mark either Celtic mid-quarter feasts, or the solstices and equinoxes, and were likely associated with ceremony, trade or political assembly (McCluskey 1990).

Comparison of the three calendar models in Table 6 shows correspondence only at winter solstice and dates around the equinoxes. The alignments coinciding with the north and south mid-declinations of the Sun in the Newgrange model fit neither the prehistoric solar model nor the mid-quarter model. But in a broader search, divisions of the solar year at times of mid-declination are, intriguegingly, found at the middle ring-cairn at Balnuaran of Clava. According to Bain, the orientation of the Western Causeway, one of three six-metre long radial stone pavements which approach the structure extant at the time of his visit, gives the bearing of the Sun as it sets on 21 April and 21 August. He noted: ‘as these dates do not correspond to any changes in the sun’s course, it is probable they may stand for some local division of the seasons, seed time or harvest. An observation taken with the sextant might throw light on this point.’ (Bain 1886–7, 130). His dates for sunset on the Western Causeway alignment exactly match the two dates given in Table 6 for sunrise shadow casting by GC3 onto GC5 at Newgrange. To check the accuracy of Bain’s claim, the author used the composite plans of the Clava cairns drawn by the Irish surveyor Boyle Somerville and which are orientated on the local meridian. The Western Causeway has an azimuth of 293°–294° scaled from those plans (Somerville 1923, Fig. 16). At the latitude of the cairn, +57° 28′, and using an estimated horizon altitude of +1°, the indicative declination δ is about +12°. This corresponds to 21 April and 21 August, confirming Bain’s alignment claim but leaving unanswered the question of intentionality, meaning and probability. Bain did suggest, however, that all three radial causeways had the purpose of dividing the year into periods,

[10] The festival of *Imbolc* marked the start of spring, coinciding with the feast day of St. Brigit on February 1 (anniversaries of Saint’s deaths were commemorated from early in the Christian era). The name *Brigit* could reflect the name of the pre-Christian goddess *Brig; Imbolc* is believed to be of Celtic origin possibly meaning ‘in the belly or womb’. Another interpretation may mean ‘with milk’. The festival of *Beltaine* (*Bealtaine* is Gaelic for the month of May) marked the beginning of summer and was noted for the use of fire to ward off diseases in cattle. The festival of *Lughnasa* is associated with the pre-Christian god *Lugh* (*Lúnasa* is Gaelic for the month of August). This assembly marked the beginning of the harvest. The festival of *Samhain* marked the end of the year and made time for repletion and relaxation (*Samhain* is Gaelic for the month of November). *Samhain*, celebrated on November 1, is the predecessor of All Souls’ Day, Halloween, and a notable time for veneration of the dead.

raising the possibility that similar examples may await discovery in the archaeological record at other similar sites.

TABLE 6. Comparison of prehistoric calendar models and Early Medieval festival dates.

Notional date	δ	Newgrange shadow casting	Prehistoric solar calendar	Mid-quarter days
December 21	−23° 59′	Winter solstice	Winter solstice	-
February 1	−17° 21′	-	-	Imbolc
February 18	−12° 00′	Mid-dec. (S)	-	-
March 20	±0° 00′	Vernal equinox	Vernal equinox	-
April 21	+12° 00′	Mid-dec. (N)	-	-
May 1	+15° 15′	-	-	Beltaine
June 20	+23° 59′	Uncertain	Summer solstice	-
August 1	+17° 59′	-	-	Lughnasa
August 21	+12° 00′	Mid-dec. (N)	-	-
September 22	±0° 00′	Autumnal equinox	Autumnal equinox	-
October 24	−12° 00′	Mid-dec. (S)	-	-
November 1	−14° 30′	-	-	Samhain
December 21	−23° 59′	Winter solstice	Winter solstice	-

Conclusions

This interdisciplinary study argues the hypothetical use of the Great Circle at Newgrange as a low-precision solar construct for predicting and tracking seasonal time in the Bronze Age. A broad range of approaches and tools are used to analyse the data, mindful of: ‘the ever-present danger of projecting the experience of modern mathematics and technology onto artefacts of what must be considered an alien culture.’ (Angell 1976). Moreover, there are inherent risks in retro-fitting modern perspectives and unintended biases to infer meaning in a prehistoric structure whose intended purpose may have differed entirely from that which is proposed by the author. Obviously, there is no explanatory ethnographic record. Nor is there any equivalent published case study known to the author at the time of writing. What is clear, however, is the undoubted organisational ability of the community who acted with a common aim to erect the monoliths. Nor is there any doubt as to the engineering skills required to quarry, transport and position gigantic stones into carefully selected sockets surrounding, in this case, a pre-existing iconic cairn (see Atkinson 1961, for a discussion on Neolithic engineering skills).

The research methods are quantitative and based on accurate field survey techniques, numerical processing and testing. The levels of accuracy and computational precision are consistent with the aims of the task. Azimuths and astronomical declinations are therefore quoted to the nearest minute of arc, the convention of the discipline. The quoted precision, however, could be relaxed by rounding to the nearest degree of arc without any significant effect on outcomes or conclusions. The

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author would strongly argue that prehistoric people who farmed in the Boyne Valley, or beyond, would only have needed to discern the Sun on the horizon to a precision of a diameter or two at best, one solar diameter being about half a degree of arc. This would suggest that a small sector of the horizon, easily discernible to the naked-eye, was of interest and symbolic importance rather than any exact direction.

Summarising the findings, the positions of the largest monoliths have been shown to cluster around the entrance of the passage tomb, an area of undoubted special interest for the users of the monument in the Bronze Age. The sector running clockwise from GC17 to GC−10 is devoid of monoliths and, interestingly, delimits the horizon beyond the northerly extreme rise and set directions of the Sun and Moon. This same sector also frames the region of sky containing the perpetually visible circumpolar stars. The spatial analysis negates the idea of the ring fitting circular form. The locations of three of the monoliths in particular, GC1, GC-1 and GC-2, could suggest their deliberate and careful positioning so as to realise recurring shadow casting considered meaningful in the annual solar cycle. The research demonstrates how the dominant three-spiral motif on the left-hand side of the obverse face of K1 is consistently targeted by sunrise shadow casting on astronomically interesting dates. The manner in which the three-spiral motif is repeatedly targeted by the shadows at these times further suggests this elaborate and intricate element of megalithic art was focal to the community at that time.

After the vernal equinox, shadow casting onto K1 ceases as a phenomenon until the Sun's return on the autumnal equinox. Following the vernal equinox, the dawn shadow cast by GC3 aligns with GC5 on dates which symmetrically fit the calendar model discussed in the text. No attempt is made to infer one-day precision in terms of any deliberate usage. Instead, the widest bounding temporal limits are shown. Recorded site photography calibrates and verifies computer simulations of the phenomena. The statistical analysis rejects the null hypothesis but caution is advised due to the small size of the data sample, the criteria used for parameter selection, and the uniqueness of the phenomena in a Bronze Age or any other chronological context.

The findings raise many research questions for future consideration. Were the monoliths merely positioned so as to surround the cairn for a purpose entirely different to that which is suggested here? If the calendrical hypothesis is a valid interpretation, were the monoliths used as gnomons to predict and mark seasonal divisions of the year associated with auspicious periods having ceremonial, religious or ritual significance? One of the aims in this paper has been to address what Prof. O'Kelly first described as the prevailing interest in the astronomical possibilities alleged to be inherent in the Great Circle. Another is to document the phenomena for scientific record, noting how the shadows have not significantly changed alignment in the intervening millennia since the Bronze Age. This, despite the small angular alteration in the obliquity of the Earth's axis of rotation.

A fuller interpretation of this work will await critical review, the possibility of similar examples being discovered at other archaeological sites, and innovative thinking on this type of data. Nonetheless, when witnessing these phenomena in the present, and having shown their alignments to be immutable over four millennia, we can continue to view and experience scenes first observed in the Bronze Age – a profound thought, at the very least.

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