Planetary Nebula NGC 6543 as the Source of the Spikes of Cosmic Rays Recorded in the Greenland and Antarctic Ice Cores

Aden Meinel[1,2] and Marjorie Meinel[3]

[1] Professor emeritus, U. Arizona, Tucson, AZ `ammeinel@cox.net`
[2] Distinguished Scientist, retired, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
[3] Senior Scientist, retired, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

Summary. Cosmic rays (CRs) originate deep within the Galaxy and are shown by observations from satellites to be arriving equally from all directions in space. Searches looking for departures from a uniform arrival pattern have shown only traces of directionality. Thus when we reported in 2005 that we saw a signature in the flux pattern of CRs arriving from a point source in the Greenland ice core ^{10}Be archives we were told by knowledgeable persons that the variations of CRs in the ice cores were fully explained by variations in the geomagnetic field acting on a uniform spatial distribution of CRs. However we had noticed variations bearing the signature of the 21 Ky period of precession. We knew that precession would have no effect on a uniform distribution of CRs. So our challenge was to determine if our interpretation of this curious signature was correct, and if so, to see if the signature gave a clue to the location of this celestial point source of CRs. We have identified the source object as NGC 6543 and show that the variations of the CRs emitted during the past 800 Ky fit with the expected aging of planetary nebulae (PNe).

Key words: Planetary Nebulae: NGC 6543; cosmic rays

1 Basic data

The basic data are shown in Fig. 1. Time flow in ice core chronology is conventionally presented with increasing core depth toward the right, thus time flow is toward the left. The flow of time in Fig. 1 is toward the right as is customary in astronomy wherein we are concerned with the time sequence of events affecting the flux of CRs. The coordinates are linear in each case, with zero indicated by the axes labeled A, B, and C. Fig. 1A shows on a linear time scale the variation of ^{10}Be, proxy for CR flux, corrected for the variation of annual accumulation of ice. In making this correction for the effect of dilution by snowfall it is necessary to use the amount of accumulation measured at *exactly* the same depth in each core segment as is the measurement of ^{10}Be. This is necessary to minimize the meteorological noise caused by year-to-year variations of actual precipitation. After correction for snowfall variations the cosmic rays flux is essentially flat, but with sinusoidal oscillations between 70 and 30 KyBP (Kilo years Before Present), a key signature in this analysis. Fig. 1B shows the variation of the surface geomagnetic field strength [1]. Visual examination suggests an inverse correlation between the surface field strength and the flux of CRs. Changes in the dipole field strength obviously will affect the arrival pattern and attenuation of CRs. That the correlation isn't better suggests an alternate explanation as we discuss herein. Fig. 1C shows the effect of variation of lunar-solar precession on insolation showing a period ~21 Ky [3]. The apparent agreement of the ~21 Ky period of the oscillations of CR flux in Fig. 1A at 50 KyBP with the oscillation period in the precession curve is an important clue that the ^{10}Be count has been affected by precession. There are only two oscillations in the CR flux while the precession oscillations are continuous, a key issue that directly leads to the determination of the right ascension and declination of the source.

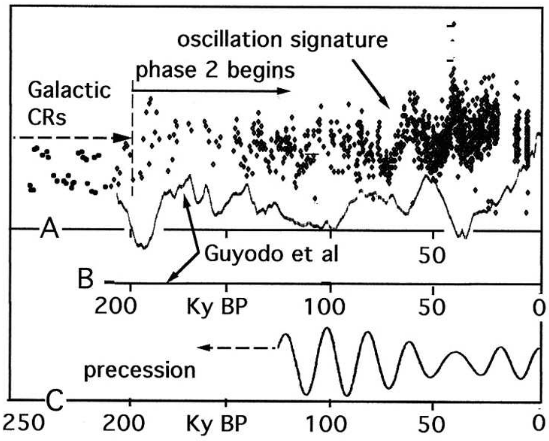

Fig. 1. Time variation of the surface geomagnetic field strength.

1.1 Attenuation of CRs by precession

The celestial position of a point source of CRs will change as a result of the combined effect of lunar-solar precession, ~21 Ky, and apsidal precession, ~120 Ky. The result is a path consisting of ~6 precession loops as shown in Fig. 2A. The constant flux emitted by a point source will then be attenuated as a function of the apparent latitude of the source. The arrival directions of individual CRs, however, are completely scrambled upon encountering the dipole magnetic field of the Earth. We can, however, derive the source RA and Dec from the modulation pattern of the CR flux induced by the geomagnetic field. The example in Fig. 2 is for a point source at 18h+65° . The time-variation of latitude is shown by the length of the lines between points equally spaced in time, also plotted as vertical lines in Fig. 2C. In the absence of information on the energy distribution of CRs from the unknown source we assumed it was the same as has been measured for galactic cosmic rays, simplified in Fig 2B. These lengths define a sinusoidal curve, shown in light. When the open circles are closer to the geomagnetic pole than 40° there obviously will be no significant attenuation. The result is the attenuation curve, shown in dark.

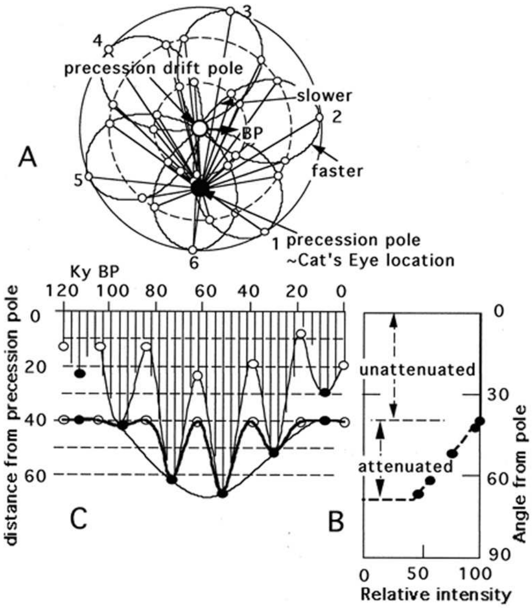

Fig. 2. Derivation of attenuation pattern from precession.

2 Identification of NGC 6543 as the source

We repeated this process for a range of RA and Dec values, resulting in the family of attenuation curves shown in Fig. 3 (left). The RA and Dec that best matches the oscillations in the CR flux gives the most probable location of the source of the CRs. The result is shown in Fig. 3 (right). Note that for every northern sky position there is a conjugate southern sky position. NGC 6543 is close to 18h+65 at a distance of ~1000 pc, while the Large Magellanic Cloud is close to the southern conjugate, but rejected as too distant to be considered as the source of a jet of CRs reaching the solar vicinity. The amplitude of the calculated attenuation curve from Fig. 3, left, has been adjusted to provide a best fit to the amplitude of the ^{10}Be oscillations in Fig. 3, right. This in turn sets a lowered level for the galactic CR flux as shown by the dashed line. This lowering is consistent with the effect of scattering the galactic CRs by the magnetic field of the plasma from NGC 6543, an effect discovered from the passage of plasma from solar flares. The relative amount of lowering, ~55%, is shown in Fig. 4 by the change between the galactic flux from the Antarctic data, light dashed line, and the heavy dashed line.

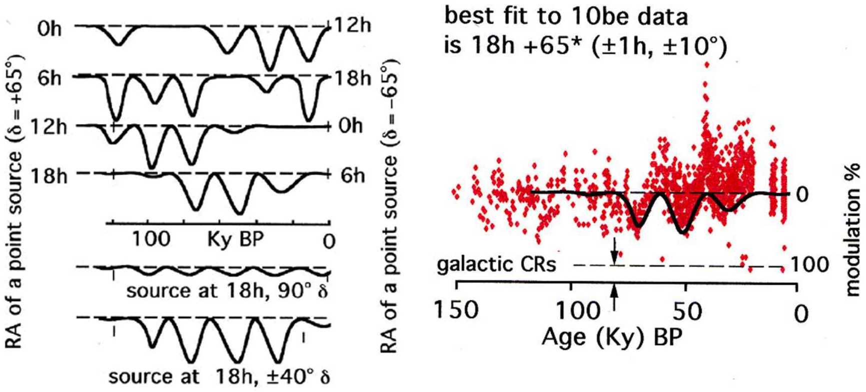

Fig. 3. **Left**: variation of attenuation profiles for a range of RA and Dec. **Right**: Best fit of CR data is for 18h+65°= NGC 6543.

2.1 Orbital configuration

In the hypothesis that NGC 6543 has a binary central star with an accretion disc that produces a polar jet of CRs pointing toward the Earth, then the orbital plane of NGC 6543 would be normal to the line of sight. This is consistent with the central object showing no variation of radial velocity. We also assume that the the orbital axis is orthogonal to the Lagrange L2 and L3 points of the Roche equipotential surfaces of a close binary [2].

2.2 CR spikes

The CR pattern between 45 KyBP and 30 KyBP, when viewed at higher resolution, suggests that the entire pattern in Fig. 4 (top) could be comprised of discrete spikes of CRs. Confirmation of this interpretation of discrete spikes came when the data from the EPICA Dome C site between 800 KyBP and 700 KyBP was published in December 2006. This data in Fig. 4 (bottom) shows well resolved strong spikes of CRs, especially near 700 KyBP. Our first thought was that this was evidence of another active object. If so its pattern was distinctly different from that of NGC 6543. This data does not in itself show any signature that could be used to indicate where in the sky to look. We couldn't find a candidate object even in the southern celestial sky. Then it dawned on us that this different appearance could be NGC 6543 but at an earlier stage in its development. To resolve this uncertainty we took three things into consideration. First, the age of the outermost halo of NGC 6543 is thought to be no older than 200 Ky. Second, there is no remnant nebulosity from an earlier activity. The presence of these spikes and absence of earlier nebulosity is consistent with the accepted model for the aging of a close binary star of high mass, an AGB, thus strengthening the conclusion that NGC 6543 is also the source of the spikes in the Dome C data. Third, there is no other active object close enough to be responsible for these strong CR spikes. Thus NGC 6543 becomes the logical source of the CRs also recorded in the Antarctic ice. The authors of the Dome C paper, however, suggest that these spikes are a previously unknown effect of re-crystallization of ice

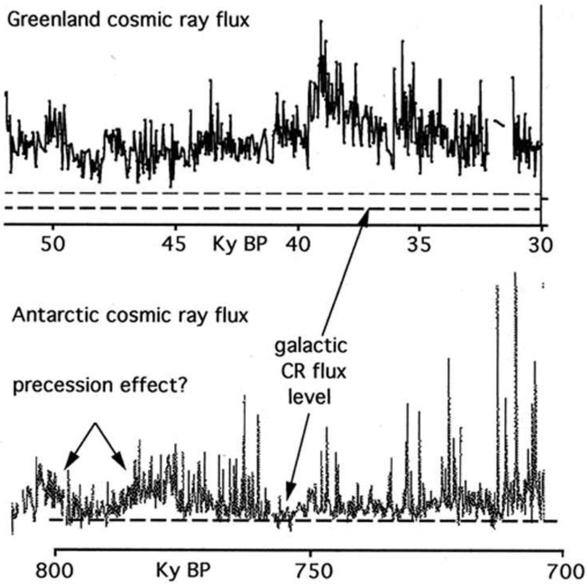

Fig. 4. Evidence for spikes of CRs during the past 800 Ky.

under high pressure, sweeping the ^{10}Be ions into interfaces between re-crystallized regions. We favor a different explanation based on the nature of a spike event. The duration of a spike event is important. It could be a very brief event at the accretion disc, possibly a fraction of a second. A range of energies of the CR particles in the spike event plus the travel time of ∼3000 years would spread out their arrival times to decades. Their spread could also be affected, but to a much lesser degree, by the rate of deposition of ^{10}Be onto the ice. Even so, it would be interesting to have the profile of ^{10}Be within the length of an ice core to see if there is fine structure that could aid in understanding the details of the ejection of a spike. Which attribution is correct, re-crystallization or abrupt spike onset, will be settled when the pattern of spikes of ^{10}Be for the 800-700 KyBP age-depth from the ongoing CSCAR Dome A drilling program can be compared with the pattern from Dome C. The two sites are ∼1000 km apart, thus our interpretation would be confirmed if the same generic pattern of spikes is found.

2.3 Magnetic field issues

The magnetic field associated with the jet will vary with distance by the ratio of the diameter of the jet at the accretion disc (∼10 km) to the diameter of the 22 pc (∼E15 km) footprint at the Earth. This means that the field at the Earth is diminished by a factor of ∼E-14. This factor has an interesting consequence regarding perturbations to the geomagnetic field by surges of the magnetic field accompanying the CRs. It is known that the passage of plasma and CRs from the Sun carries a magnetic field strong enough to perturb the geomagnetic field, as during a magnetic storm. Thus we raise the possibility that the pattern of variations of the surface geomagnetic field, shown in Fig. 1B, is the result of the variations of the CR flux from NGC 6543 and its associated magnetic sheath. If so, then the linear rise of the geomagnetic field since ~30 KyBP could be the result of the Earth exiting the footprint of the CRs. Alternately it could be consistent with NGC 6543 ceasing its activity in producing CRs. These two possibilities are also consistent with the monotonic decrease in production of both cosmogenic ^{14}C and ^{10}Be shown in Fig 5. We suggest that Fig. 5 is consistent with our conjecture that the Guyodo record is the **result** of variations of the magnetic field accompanying the varying CR flux encountered by the Earth and not the **cause** of the CR variations. Fig. 5 indicates that the CR flux has now returned to the level set by the galactic CRs while the geomagnetic field strength is at the highest level in the past 200 Ky consistent with the end of this encounter with CRs from NGC 6543.

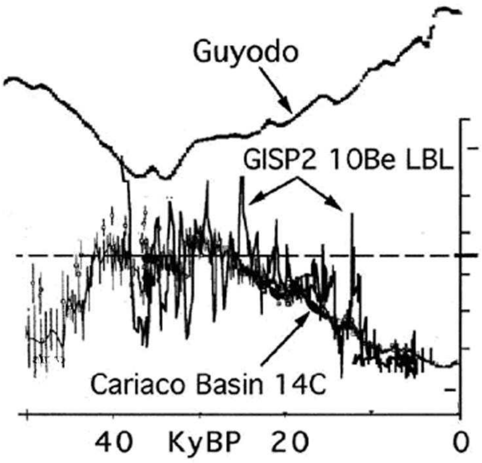

Fig. 5. Earth apparently exits footprint of CR jets or NGC 6543 becomes quiet

2.4 Evolution of the close binary star

Perhaps the most interesting result of our interpretation of the CR chronology is that the change of the appearance of the fluctuations and spikes of CRs agrees with the theoretical evolution of a typical close binary star. The ice core data suggests that there are two major phases in which a surrounding nebulosity is formed. The first is when the more massive companion, S1, of perhaps 5 $M_{\odot}$, ejects its envelope. Being a binary this stage probably would be considerably different from that of a single star, but still a nebulosity would be ejected as a multiple sequence of lesser surges of plasma. Any cosmic rays probably would be ejected into a wide cone angle analogous to that observed for the Sun, none surviving passage as a collective entity to the solar vicinity. S1 would end as a very low luminosity compact object, a neutron star or small black hole depending on the final mass. A sudden mass loss of

S1 could result in perturbation of a circular orbit into an elliptical orbit, the result of a mismatch of the orbital velocity of S2 with respect to the combined mass of S1 and S2. The nebulosity formed at this stage would be dissipated into space before the next event occurs.

An interim phase begins when the lower mass companion, S2, begins to evolve into the Giant Branch. Its expanding atmosphere would result in occasional mass transfer to S1 via L, presumably leading to the formation of an accretion disc, a necessary condition for the ejection of a collimated jet of cosmic rays. At this point no significant nebulosity would be formed. We interpret the spikes of cosmic rays recorded between 800-700 KyBP as indicating that NGC 6543 was in this stage.

The second phase involving formation of a PN is when S2 also completely looses its envelope. The jets of cosmic ray are reduced in intensity but become almost continuous while emissions of plasma from S2 through L2 and L3 forms the surrounding nebulosity. We interpret the pattern of cosmic rays between 200 KyBP and the present as indicating that NGC 6543 was in this stage.

References

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