to the southwest of its present position. This is well outside the boundaries of the Gemini constellation, so that the present name could not have been given at birth. In view of the small distance involved, it is probably difficult to search for a supernova remnant which may well now include the Earth. But if Geminga was generated in a supernova explosion liberating a huge amount of energy at 100 pc or so from the Earth, the environmental effects could have been considerable.

As to the physical nature of the optical emission, these data add no information, except for the possible constraint on Geminga's absolute magnitude. Thermal as well as nonthermal mechanisms may contribute to the emission (see, for example, ref. 20), which could be pulsed at 237 ms, with an unknown duty cycle. The period-luminosity dependence originally proposed by Pacini[21], and discussed more recently in ref. 22, can be applied, assuming for Geminga an optical duty cycle similar to that of the Vela pulsar, as is the case at higher energies. This yields an $M_v \approx 28$ which would place Geminga at ~3 pc, a distance corresponding to an improbable space velocity vector. From the γ-ray data and from the pulsar's measured rotational energy loss, an independent absolute upper limit of ~400 pc distance can be estimated.

An image of Geminga with the planetary camera on the HST is planned for the near future, to pinpoint the position of G″ to the best possible accuracy allowed by its current point spread function. Repeating such measurements six months apart might lead to a parallax measurement for Geminga, something which cannot be easily done from the ground for such a faint object. The predictable direction of the annual parallactic displacement will help to disentangle it from the known proper motion, and its magnitude will solve the problem of a precise distance measurement. □

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The Geminga supernova as a possible cause of the local interstellar bubble

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THE Solar System resides at the edge of a cavity of hot (10^6 K), low-density (5×10^{-3} cm^{-3}), X-ray emitting gas embedded in the interstellar medium[1–4]. This void, sometimes called the Local Bubble, is thought to be less than 10^7 years old, but its origin is unknown. Here we propose that the void was caused by the supernova that produced the Geminga pulsar. The initial identification[5] of Geminga as a pulsar, and the subsequent detection[6–8] of pulsations in high-energy γ-rays, give an age of 3×10^5 years and a pulsar distance in the range 40 to 400 pc (refs 6, 7). Using this information, and the recently discovered[9,10] proper motion of a likely optical counterpart, we find that the supernova was well positioned to produce the local void, provided that the explosion occurred within about 60 pc of the Solar System. Larger distances are not excluded by our analysis, but they would put the supernova at a position for which there is no evidence for such an energy input.

Geminga, discovered by SAS-2 in the early 1970s[11] and subsequently detected by COS-B[12], is one of the brightest high-energy (>100 MeV) γ-ray sources in the sky, but its nature remained a mystery for 20 years. During this period a tentative X-ray counterpart, 1E0630+178, was found[13], as well as three possible faint optical counterparts denoted G (refs 14, 15), G′ (refs 16, 17) and G″ (refs 18, 19). The Geminga mystery was solved in 1992 when 1E0630+178 was from Rosat X-ray data found to be a pulsar. The 237-ms period was then detected in the γ-ray emission from Geminga using data from GRO/EGRET[6], COS-B[7] and SAS-2[8].

Pulsars are neutron stars born at the core of type II supernovae. The ~1 $M_\odot$ (1 solar mass) iron core of a massive progenitor star collapses to form a rapidly spinning and highly magnetized neutron star, while the $>8M_\odot$ outer envelope is ejected with high speed (>1,000 km s^{-1}). In some cases, slight asymmetries in the explosion cause the neutron stars to be ejected at a speed of >100 km s^{-1} (ref. 20).

The Geminga pulsar turns out to be young and remarkably nearby. The characteristic age, calculated by dividing the period by twice the period derivative, is 3.2×10^5 years based on the EGRET ephemeris[6] and 3.4×10^5 years from the COS-B ephemeris[8,21]. The distance is harder to determine, but can be estimated by comparing the observed γ-ray intensity with the luminosity expected from the available spin-down energy. Uncertainties come in from an unknown beaming factor and unknown γ-ray efficiency, but reasonable values range from <40 to 400 pc (refs 6, 7).

The recent discovery[9,10] of proper motion in the G″ candidate optical counterpart of Geminga (the most likely of the three candidates[18]) allows us to trace back in time and estimate the location of the supernova and also gives a check on the distance. A proper motion 0.17″ ± 0.04″ per year was measured with components 0.10″ north in declination and 0.14″ east in right ascension (G. Bignami, personal communication). The observed motion corresponds to a pulsar transverse speed of 78 km s^{-1} at 100 pc and 314 km s^{-1} at 400 pc, so the distance to Geminga is comfortable at 100 pc and is probably not much greater than 400 pc (ref. 20). The fact that these distances fall in the range estimated from the γ-ray intensity supports the G″ identification.

The current position for the Geminga pulsar is $\alpha(2000) = 6$ h 34 min, $\delta(2000) = 17° 46'$ (refs 13, 18) ($l^{II} = 194.8°$, $b^{II} = 3.7°$). Propagating backwards 3.3×10^5 years in the opposite direction to the proper motion gives a position for the Geminga supernova of $\alpha = 5$ h 40 min, $\delta = 8° 24'$ (l^{II}197°, $b^{II} = -11.7°$). The typical uncertainty radius is 3° due to uncertainties in the proper motion and age. Figure 1 shows the possible positions for the Geminga supernova (striped region) in radial projection on the galactic plane along with contours of hydrogen column density in the interstellar medium (ISM) from ref. 3. The direction is as given above ($l^{II} = 194.8°$) with a 6° spread. The radial distance is constrained only to be greater than ~10 pc, as a closer supernova would have severely disrupted the Earth's atmosphere[22], and less than several hundred parsecs given the γ-ray brightness of

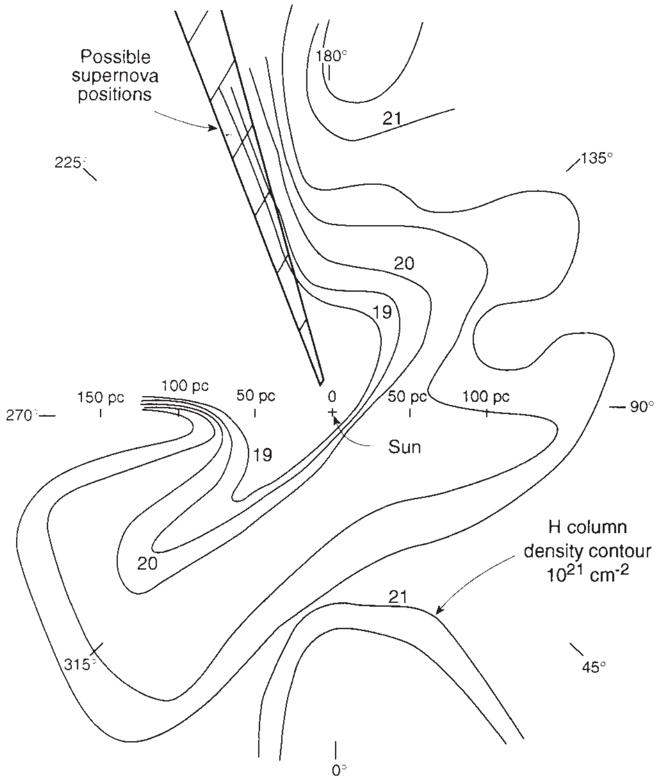

FIG. 1 Possible sites of the Geminga supernova 3.3×10^5 yr ago, shown in the striped region, projected on the galactic plane. The angular coordinates are in galactic longitude, where the Galactic Centre is towards 0°. Superimposed are the H I column density contours surrounding the Local Bubble from Paresce[3] (N(H I)$=10^{19}$, 5×10^{19}, 10^{20}, 2×10^{20}, 5×10^{20}, 10^{21}, 2×10^{21} cm^{-2}). The Local Bubble occupies most of the open space in the upper left region between the high density walls and forms an elongated structure perpendicular to the galactic plane. The Per association is towards 145° and behind the 5×10^{20} contour. The Sco-Cen associations are towards 320° behind the 10^{20} cm^{-2} contour.

the pulsar. Typical pulsar radial velocities of 100-300 km s^{-1} over 3×10^5 years imply that the supernova distance may be 50-100 pc different from that of the pulsar. The supernova direction in the figure is close to the current direction to Geminga because most of the proper motion is in galactic latitude (pulsar $b^{II}=3.7°$, supernova $b^{II}=-11.7°$).

The local cavity is apparent in Fig. 1. It has an opening towards 225° and a large-scale high-density boundary with the Perseus OB associations at 145° and the Scorpius-Centaurus association at 320°. Perpendicular to the galactic plane, the cavity extends 50-100 pc south and >100 pc north, forming an elongated galactic 'chimney'[1]. The Solar System is in fact not located directly in the Local Bubble, but is embedded in a warm (10^3-10^4 K) and medium-density (0.1 cm^{-3}) cloud of ~20 pc in size and moving away slowly (~20 km s^{-1}) from the nearby wall. It has long been a puzzle how this bubble and warm fringe were formed in the local ISM[3]. We propose that the Geminga supernova is a natural explanation for all the observed structure.

It is clear from Fig. 1 that the Geminga supernova was well positioned to create the Local Bubble only if its radial distance from the Solar System was less than ~60 pc. The lack of observed disturbances of the ISM anywhere else along the band of possible supernova sites is strong evidence that the supernova was nearby. It has been pointed out that a single supernova could be energetically adequate by itself to create the Local Bubble and fill it with hot gas if the initial ISM density in the region was relatively low (~10^{-2} cm^{-3}, ref. 1). In that case, the energy to produce the bubble is $\lesssim 3\times10^{50}$ erg, which, added to the thermal energy of the 10^6 K gas (~3×10^{50} erg), is within the range of the kinetic energy of a typical type II supernova, ~10^{51} erg. Although it may have been hard for the ejecta to propagate against the dense shell in the direction of the Sun, it was relatively easy for it to push upwards from the disk, where the density drops exponentially, to form the observed galactic 'chimney'. In the galactic plane, the Solar System is located at the inner edge of the Orion spur which stretches between the Sagittari-Carina arm and the Perseus arm[23]. Although the direction of 225° points towards a low density region of space, the density structure in the local ISM is probably more relevant to the formation of the opening in the Local Bubble.

After the explosion, the interaction of the expanding remnant with other remnants and initial mass distributions in the ISM evidently caused the pocket and steep contours near the Sun. The expansion stopped at the nearby cold, dense wall and all the kinetic energy was converted to thermal energy. The outer layer of the wall was evaporated by gas at 10^6 K (ref. 24) and formed the observed warm cloud surrounding the Solar System. The warm gas expansion velocity of ~20 km s^{-1}, and the total mass evaporated during the last 3.3×10^5 yr, ~100 $M_\odot$ according to the evaporation theory[24], are fully consistent with the observed values[3]. The warm and hot regions have now reached pressure equilibrium.

The Geminga supernova is a unique phenomenon in astrophysics. As a type II supernova occurring 3×10^5 years ago at a distance of 60 pc it would have been as bright ($m\approx-13$) as the Moon. It created (1) a pulsar that is one of the brightest sources in the γ-ray sky, (2) a void filled with hot gas in the local ISM that permits extreme ultraviolet observations of nearby stars, (3) a galactic chimney above the disk and an opening in the local ISM and (4) a three-component interstellar medium structure in the solar neighborhood.

Note added in proof: New studies of the X-ray spectrum and flux indicate that the Geminga pulsar distance is between 150 and 400 pc[25], which implies a radial velocity of >250 km s^{-1} for a supernova distance of <60 pc. □

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