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AN IDENTIFICATION FOR "GEMINGA" (2CG 195+04) 1E 0630+178: A UNIQUE OBJECT IN THE ERROR BOX OF THE HIGH-ENERGY GAMMA-RAY SOURCE[1]

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ABSTRACT

In the search for counterparts for *COS B* high-energy gamma-ray sources, 2CG 195+04 was covered with two *Einstein Observatory* IPC exposures and one follow-up HRI pointing. In a 10^4 s observation, four serendipitous sources have been found, three near to the detection limit and one, 1E 0630+178, at a flux level of approximately 2×10^{-12} ergs cm^{-2} s^{-1}. The 3″ HRI position has permitted an optical identification with a faint blue object, while VLA data at 6 cm do not show radio flux at the HRI position.

The object appears to be unique on the basis of its observational characteristics, mainly the $L_x/L_v \approx 1000$, the lack of a radio counterpart, and the absence of temporal variability and of spatial extent in the X-ray data. Moreover, the very small interstellar absorption suggests a distance of the object of approximately 100 pc (or less).

Because of the peculiarity of the X-ray object (which has an *a priori* probability of a few percent of being in the *COS B* error box), we propose it for the counterpart of 2CG 195+04, "Geminga." Among known celestial objects, only a neutron star seems to come close to meeting the data; however, its characteristics would be different from those known so far, due to its detection through the γ-ray and X-ray channels and to the lack of any pulsation.

Subject headings: gamma rays: general — stars: neutron — X-rays: sources

I. INTRODUCTION

The second *COS B* catalog of high-energy (> 100 MeV) γ-ray sources (Swanenburg *et al.* 1981) lists 25 objects which appear as both significant and unresolved excesses in the γ-ray sky. The majority of them are galactic in nature, as shown by their celestial distribution, and are as yet unidentified. Two sources identified with certainty by their timing signature are the Crab and Vela pulsars, while excess γ-radiation can also be associated, with a high degree of confidence, with local interstellar cloud complexes, under very different emission scenarios. For a recent review of many aspects of galactic γ-ray sources, including a history of previous counterpart searches, the reader is referred to Bignami and Hermsen (1983).

One obvious way to search for counterparts is to explore the *COS B* error circles at the other wavelengths and then to analyze potential candidates individually. This was done at X-ray wavelengths using the opportunity provided by the *Einstein Observatory* (Giacconi *et al.* 1979) Guest Observer program. As discussed in detail by Caraveo (1983), a good coverage was obtained for many *COS B* sources down to a flux limit of approximately 10^{-13} ergs cm^{-2} s^{-1} in the IPC energy range from approximately 0.1 to 5 keV.

In this *Letter* we present the complete investigation of the source 2CG 195+04 ("Geminga"), leading to the discovery of a strong candidate for its counterpart at X-ray and optical wavelengths. This candidate has not previously been reported, although in the same region of the sky Lamb and Worrall (1979) have presented an *HEAO 1* A-2 result on a weak source with a wide error box.

Geminga[2] is the brightest unidentified source in the *COS B* catalog with a flux of approximately 5×10^{-6} photons (> 100 MeV) cm^{-2} s^{-1}, approximately 2.4×10^{-9} ergs cm^{-2} s^{-1} in the interval from 50 MeV to 3 GeV (Masnou *et al.* 1981). The source, discovered during the *SAS 2* mission (Fichtel *et al.* 1975), was re-

[1]The X-ray data used in this *Letter* were collected as a part of the Guest Observer Program of the *Einstein Observatory*.

[2]The reader may be puzzled about the origin of the name "Geminga": this source is in the constellation of *Gemini* and it is a *ga*mma-ray source. Pronounced with both G's as in "get," the word means "does not exist" or "it's not there" in Milanese dialect.

peatedly observed by *COS B*. No long-term variability was found. Early reports of a periodicity of approximately 1 minute were later disclaimed (Masnou *et al.* 1981). With the low photon fluxes of γ-ray astronomy, it is not possible to search for unknown fast, i.e., pulsar-like, periodicities.

The complete γ-ray error box could be contained in a single *Einstein* IPC field, providing a unique opportunity for an in-depth search in the keV region. The several sources found were investigated at radio and optical wavelengths, leading to some identifications. In this respect, the recent result of Sieber and Schlickeiser (1982, hereafter SS82) is also very relevant, since they present and discuss a radio map of the same γ-ray error box.

II. X-RAY SOURCES AND THEIR IDENTIFICATION

Three observations of the Geminga region of the sky were performed with the *Einstein Observatory*, two with the IPC instrument (IPC 1: 1979 September 20, useful time 2401 s; IPC 2: 1981 March 17, useful time 8361 s) in the focal plane and one with the HRI (1981 March 18, useful time 2411 s).

Since the pointing directions of the two IPC fields coincide, we have summed the two. The combined IPC image is shown in Figure 1*a* (Plate L3), where the "unmasked" raw data can be seen.

First, one notes that neither in the raw data nor in more smoothed versions of the images is it possible to see evidence of diffuse X-ray features. On the other hand, four sources exceed a 5 σ threshold and are well visible in Figure 1*a*, where they are numbered from 1 to 4. Table 1 gives a comprehensive summary of the source data relative to the two IPC observations. Figure 2 (Plate L4) shows a moderate blowup of the region in the red POSS print which can be used as a finding chart for the four IPC positions, shown as circles with a 1′ error radius. For a discussion of sources 1, 2, and 3, see the legend to Figure 1.

Source 4 is by far the brightest in the field, so that it is possible to present results on its spectral properties and of a search for temporal variability and spatial extent. The source spectrum is very soft, with the majority of the counts below approximately 1 keV, and with little evidence for interstellar absorption. An acceptable fit (reduced $\chi^2 \sim 1$) was obtained equally with power-law ($3 < \alpha < 3.5$) exponential ($0.1 < kT < 0.4$) and blackbody ($0.08 < kT < 0.1$) spectra. However, in no case could the maximum allowed column density N_H to the source exceed 2×10^{20} cm^{-2}, implying a very low interstellar absorption. In fact, for all the spectral types considered, the data were best fitted by N_H in the 10^{19}–10^{20} cm^{-2} range. Naturally, it is also possible that a different, more complex spectral shape at the source mimics the lack of interstellar absorption. It is to be noted that, for each different law used to describe the spectrum of the source, a slightly different total flux value can be assigned to the source (i.e., 1.6–2.2 $\times 10^{-12}$ ergs cm^{-2} s^{-1}) with respect to that estimated by the count rate and given in Table 1, stressing that the errors associated with the latter are only of a statistical nature. A special case of spectral fit to the data can be tried with a monochromatic line; in our case, a good χ^2 value was obtained for a line centered at approximately 260 $\pm$ 20 eV.

An analysis was performed on the temporal behavior of the source (1E 0630+178). The constancy of the "crude" flux in IPC 1 and IPC 2 is well within the instrument stability. The HRI data for this source (see below) confirm this statement within their limited statistics and considering the different energy responses.

Short-term random variability was investigated using as input the count rates for both the source and back-

TABLE 1

SOURCE PARAMETERS

	α(1950) δ(1950)		FITTED COUNTS		USEFUL TIME (s)		FLUX ESTIMATE[a] (ergs cm^{-2} s^{-1})	
SOURCE	IPC 1	IPC 2	IPC 1	IPC 2	IPC 1	IPC 2	IPC 1	IPC 2
1	...	6°33′22″.7	...	19	...	5087	...	$1.3 \pm 0.4 \times 10^{-13}$
	...	18 3 47.5						
2	$6^h31^m31^s.6$	6 31 36.2	17	26	1647	5456	$2.4 \pm 0.4 \times 10^{-13}$	$1.1 \pm 0.3 \times 10^{-13}$
	18 18 58.3	18 19 59.3						
3	6 31 12.9	6 31 12.2	21	71	2073	7086	$2.3 \pm 0.4 \times 10^{-13}$	$2.3 \pm 0.3 \times 10^{-13}$
	18 1 4.5	18 1 52.8						
4	6 30 59.6	6 31 0.9	214	821	1929	6692	$2.1 \pm 0.1 \times 10^{-12}$	$2.2 \pm 0.07 \times 10^{-12}$
	17 48 34.1	17 48 34.1						

[a]Derived directly from the count rates. Since the true fluxes are spectrum and absorption dependent, the values given must be regarded as indicative. More details on the source 4 spectrum and flux are given in the text.

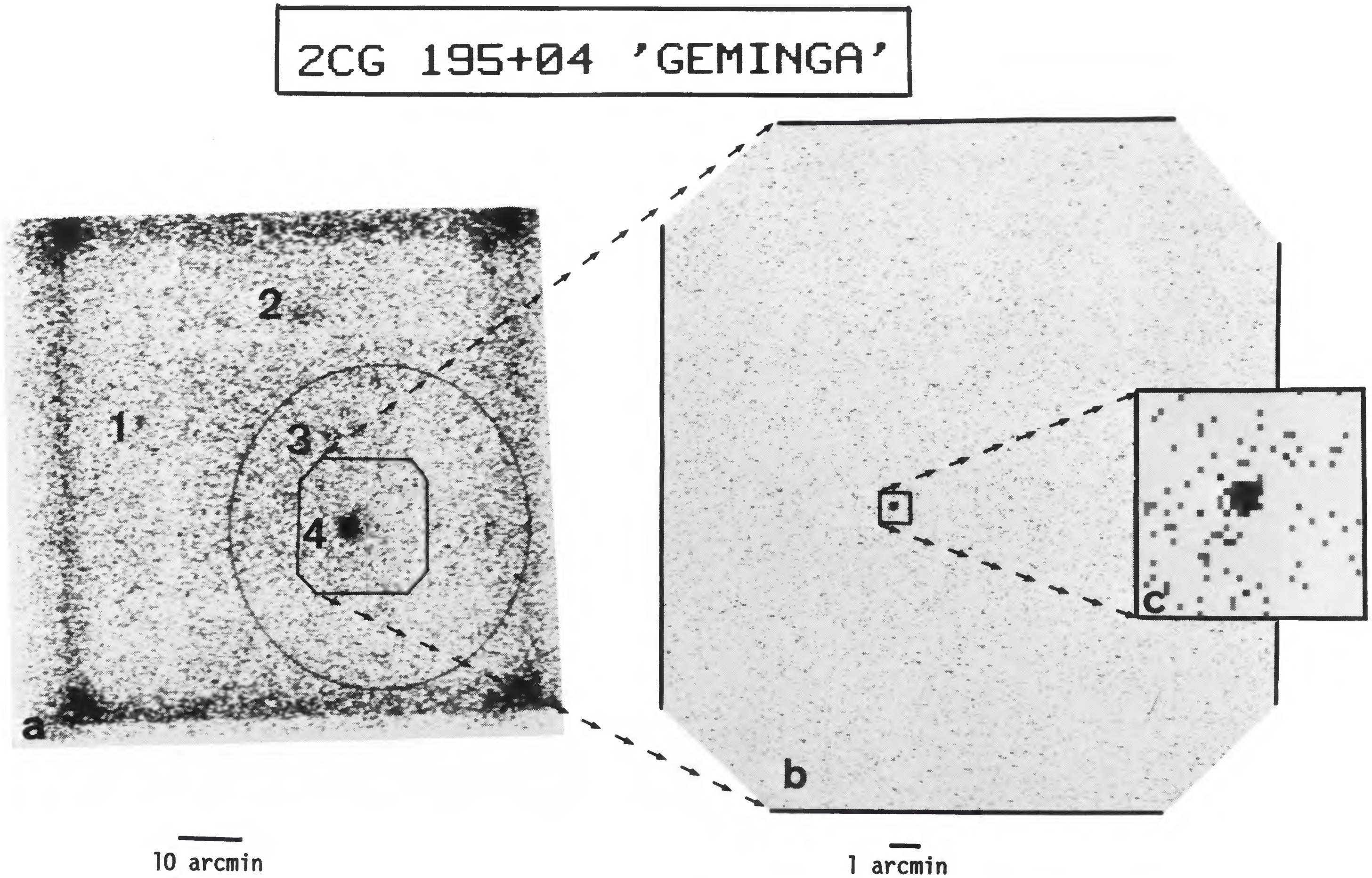

FIG. 1.—The X-ray data, shown in increasing resolution. (*a*) The extended IPC field (N at top, E at left) sum of IPC 1 and IPC 2. The dark corners are a detector artifact appearing when the extended IPC field is required, as are the white shadows of the counter "ribs," showing up well in this long exposure. The new sources, numbered 1–4, are well visible. Source 1 is only visible in IPC 2 since it is too faint for IPC 1. The brightest optical object in its error circle is a stellar one of $m_v \sim 12$. If this object were associated with the X-ray source, its F_x/F_v value of $\sim 3 \times 10^{-3}$ would be compatible with one due to stellar corona emission for a wide range of spectral types, from A to M (Vaiana *et al.* 1981). Source 2 is the only source for which a definite claim of X-ray variability can be made, as evident from Table 1. More apparent in the hard channels, it is associated with a structured radio source in the 6 cm map of SS82. Further observations carried out at the VLA by one of us (R.C.L.), together with optical work will be published elsewhere. Source 3 seems to show, within the limited statistics due to its faint flux, a soft spectrum. The lack of an HRI pointing, as well as of any prominent feature in the finding chart, does not allow any identification proposal. No radio flux is seen in either the SS82 map or the VLA, down to ~ 1 mJy at 6 cm. Source 4 is discussed in the text. The *COS B* error circle for 2CG 195+04 ("Geminga") is also shown. (*b*) The HRI field, showing 1E 0630+178 and no other source or extended feature in its vicinity. (*c*) Detail of the HRI field (1′ × 1′) showing the pointlike nature of 1E 0630+178 ("Geminga").

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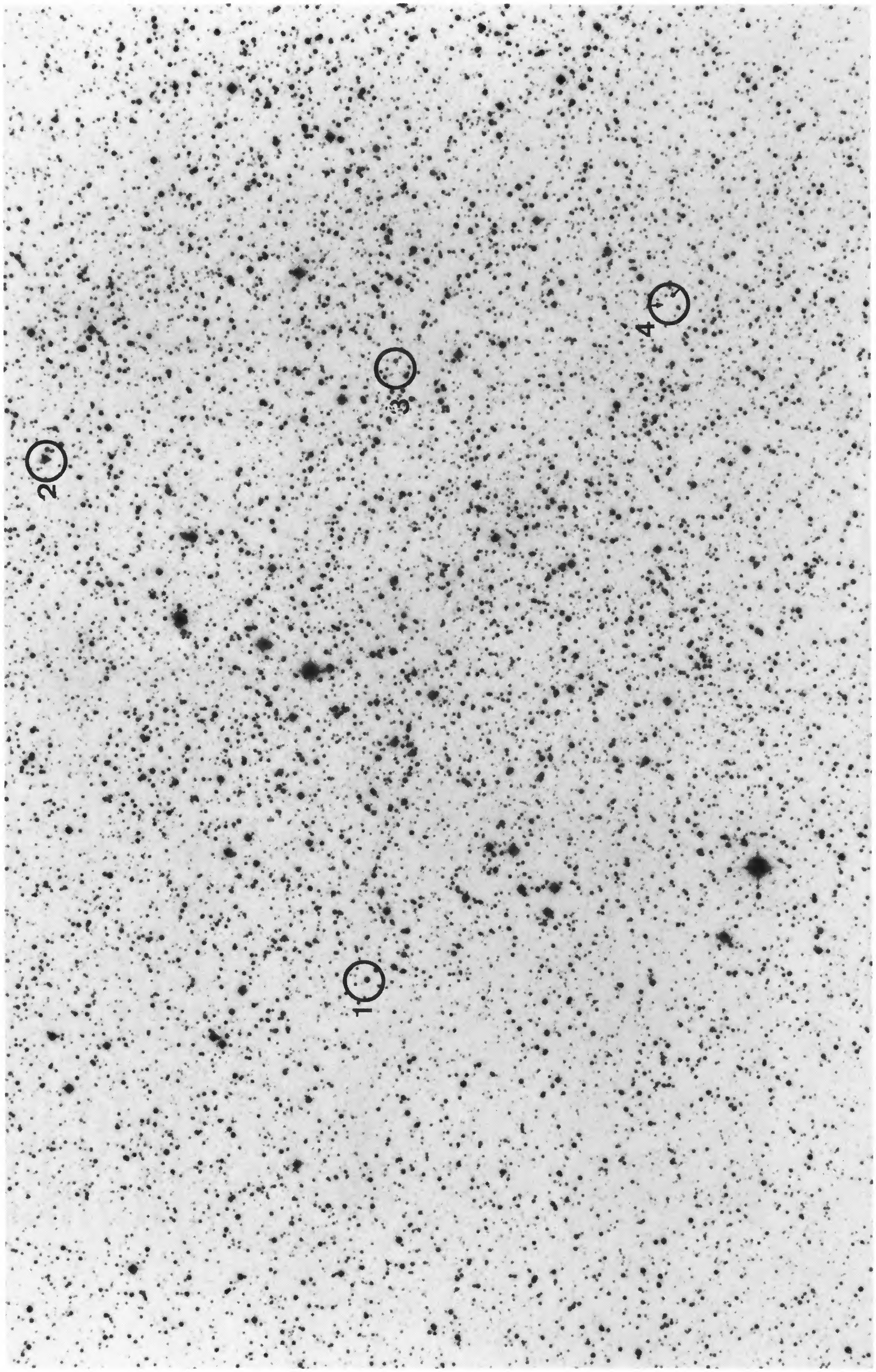

FIG. 2.—Moderate blowup of the red POSS plate (1470) covering the source region of the IPC field. The positions of sources 1–4 are shown with their IPC uncertainty of ~ 1′ radius, usable as finding charts. The HRI position (shown by arrows) for 1E 0630+178 is also shown, pointing to a blank field.

BIGNAMI, CARAVEO, AND LAMB (*see* page L10) ground binned in intervals from minutes to hours. No evidence of source variation was seen. A search for periodicities was also performed using the FFT algorithm in the second to millisecond range. The frequency interval covered was quite extensive, and, in particular, period values down to 2.6 ms were included. No significant effect was found.

The source 1E 0630+178 was also investigated with an HRI exposure as shown in Figure 1*b*. The final (i.e., "reprocessed") best position for the source is

$$\alpha(1950) = 6^{h}30^{m}59^{s}.15, \quad \delta(1950) = 17°48'33''.0,$$

to which a 90% confidence radius of 3″ should be attached. A total of 90 photons were collected from the source. Analysis of the HRI image indicates that it is consistent with that expected from the instrument's point spread function; therefore, the source is unresolved (Fig. 1*c*).

The HRI error circle of 1E 0630+178 falls into a blank field on both the red and blue POSS prints. The interstellar absorption in this direction, evaluated from observations of stars, with distance moduli $\gtrsim$ 1 kpc, in the immediate vicinity ($\leq 2'$) at the Lojano Observatory (B. Marano and G. P. Vettolani, private communication) appears to be of the order of $A_v \approx 0.5$ mag. This result is fully consistent with the larger scale data of Neckel and Klare (1980). No cataloged clouds are known to cover the HRI (or IPC) position, nor is there any evidence of patchiness of the interstellar medium in the general field. The position of the source is included in the map of SS82, showing no excess at 6 or 20 cm. A more sensitive measurement from the VLA (by R. C. L.) also did not detect a source at the approximately 1 mJy level at 6 cm. A pulsar search was carried out at its position from Arecibo (Buccheri *et al.* 1982; V. Boriakoff, private communication). No evidence for a radio pulsar was found.

At our request, two CCD images of the field were obtained, one with the SAO CCD camera at Mount Hopkins, Arizona, and the other with the ESO CCD instrument at the 1.5 m Danish telescope at La Silla, Chile. In the first image, only sensitive to $m_v \approx 22$, the HRI error circle is still blank (P. Hertz and J. Grindlay, private communication). On the ESO images in the *V*, *R*, and *I*, a faint blue object is seen (H. Sol and M. Tarenghi, private communication). In the following, we tentatively assume a *V*-magnitude of approximately 23 for this object, pending more accurate estimates.

The probability of a chance occurrence of a blue object of $m_v \sim 23$ in a 3″ radius circle can be evaluated from the data of, e.g., Lasker (1976), Tyson (1981), Koo and Kron (1982), and Griffiths *et al.* (1983) to be, conservatively, 10^{-2}–10^{-3}. We are thus tentatively led to associate 1E 0630+178 with the faint blue object in its error box.

As a check on possible optical eruptive activity from the source, the standard Harvard Patrol plates were scanned. No evidence of emission was seen at the highly variable sensitivity level of the stack.

III. DISCUSSION

A number of observed characteristics combine to render 1E 0630+178 a unique object. They are: the high L_x/L_v value, which is about 1000 in the case of the optical identification (or more otherwise), the pointlike appearance of the HRI source, and the absence of any radio source in the sensitive VLA survey. To our knowledge, so far no other *Einstein* source at this flux level and with HRI positioning has a similar set of characteristics. Stocke *et al.* (1983) and Griffiths *et al.* (1983) have discussed complete optical identifications for high-latitude surveys and found no comparable source. At low latitudes, work is still in progress (Hertz and Grindlay 1981), so that it cannot be excluded that other such objects will eventually be found.

On the other hand, sources 1, 2, and 3, much weaker in flux, would appear to be compatible with a serendipitous source population expected in a 10,000 s IPC field. Naturally, source 3, unidentified and on which little information is available, cannot in principle be eliminated as a candidate counterpart for 2CG 195+04, but its probability of chance appearance in the half square degree *COS B* error circle is very high. For source 4, such probability is approximately 5%, as can be computed from the "medium" survey data of Maccacaro *et al.* (1982), taken at high latitude, and, in the absence of a more complete survey, from the data on the approximately 30 low-latitude IPC fields given by Caraveo (1983). Such probability, although indicative, is certainly not sufficient to claim an association.

However, we believe the uniqueness of the X-ray source properties to be a much stronger argument, and on that account we propose the association of 1E 0630+178 and of its optical counterpart with the *COS B* high-energy γ-ray source. The quest for elusive Geminga, started back in 1974 after the *SAS 2* discovery of the γ-ray source, comes here to an end.

As to the astrophysical nature of the object, we note that only two classes of known X-ray sources have such a high L_x/L_v value: low-mass binaries (e.g., Bradt and McClintock 1983) and radio pulsars (Helfand 1983). The first can be easily excluded, since their optical luminosity function is quite narrow and peaked around $M_v \sim 1$ (van Paradijs and Verbunt 1981). A distance modulus of $(m_v - M_v) = 22$ would place the source at approximately 250 kpc, well outside our Galaxy. More generally, the distance evaluated from the spectral data in § II weighs strongly against an extragalactic nature of the source. If the maximum permissible N_H to the source is approximately 2×10^{20} cm^{-2}, and this is compared to the total observed N_H in that direction of 4×10^{21} cm^{-2} (A. W. Strong, private communication), considering the source galactic coordinates and the galactic disk extension, one gets an upper limit to the distance of the order of a few hundred parsecs. Note that a column density comparable to such an upper limit is observed when looking at the galactic pole (Heiles, Stark, and Kulkarni 1981), i.e., through less than, say, 200 pc of decreasing gas density. Since all the best spectral fits are obtained for significantly smaller N_H values, one can realistically place the source at approximately 100 pc, and speculate on the consequences. The soft X-ray luminosity would be a few times 10^{30} ergs s^{-1} thus confirming the exclusion of a "classical" binary, in favor of low-power sources such as cataclysmic variables, extreme cases of isolated white dwarfs or hot stars, all these being naturally ruled out by the L_x/L_v value. The only type of known object satisfying the observational constraints on L_x/L_v and absolute X-ray and optical magnitudes is a pulsar, or better, a neutron star, since no pulsation is detected in our case.

If Geminga is indeed a neutron star at approximately 100 pc, from an X-ray luminosity of a few times 10^{30} ergs s^{-1} one can compute a surface temperature in the range from 2 to 3×10^5 K, for star radii from 16 to 10 km. On the other hand, the blackbody fit to the source spectral data yields acceptable temperatures only around 10^6 K, which, although too high for thermal emission from the complete surface, would be compatible with a smaller ($\sim 10^{10}$ cm^2) polar cap emitting region (Helfand, Chanan, and Novick 1980; Helfand 1983). As to the optical emission, the two temperatures given above would correspond to m_v values of approximately 25–27, much fainter than the proposed counterpart. Thus, if the optical identification is correct, it cannot be ascribed to thermal emission from the surface of a neutron star.

The X-ray data can also be fitted by a line emission at approximately 260 eV, bearing in mind the limited IPC spectral capability, especially for an off-center source. Several workers have computed the wavelength shifts expected from atomic lines in the strong magnetic fields in the vicinity of a neutron star. In particular, from calculations of Wunner and Ruder (1980), it would appear that for $B \approx 4 \times 10^{12}$ gauss, the hydrogen atom Lyman-α level is blueshifted to 250 eV.

If the X-ray source is indeed a pulsar, then, in view of current knowledge of the γ-ray sources, its association with 2CG 195+04 would become natural also on astrophysical grounds. The *COS B* spectrum of Geminga in the 50 MeV to 3 GeV interval (Masnou *et al.* 1981) shows similarities with that of the Vela pulsar. The L_x/L_v values of the objects are also similar, as would be the L_γ/L_x values which are approximately 500 for the Vela pulsar unresolved emission and approximately 1200 for Geminga.

However, arguments against an identification of a Vela-like pulsar are as follows:

1. There is a lack of a radio signal at the source position, in spite of Arecibo and VLA searches. Of course, it is possible to invoke a different beaming geometry for, e.g., the radio and γ-rays.

2. There is a lack of extension of the X-ray source. Other (not all) radio pulsars observed in X-rays show a "synchroton nebula" around them (Helfand 1983), which for PSR 0833−45 has the extent of approximately 1′ (0.1 pc) (Seward 1983) and would thus, *a fortiori*, have been resolved for Geminga. This is certainly not a strong argument, nor can this lack be the result of the very soft X-ray spectral shape of Geminga compared with that of PSR 0833−45, which appears to be definitely nonthermal (Harnden 1983). The old radio pulsars PSR 1055−22 and PSR 1642−03 also show very soft X-ray spectra (Helfand 1981; Cheng and Helfand 1983).

3. Finally, there is an absence of evidence of a supernova remnant in the region. The three young, fast, and X-ray emitting pulsars (PSR 0531+21, PSR 0833−45, and MSH 15-52, Seward and Harnden 1982) appear to be associated with radio and X-ray supernova remnants. In the case of Geminga, neither the radio map, nor the IPC and HRI data, nor the general optical field show the existence of any extended feature in the neighborhood.

In summary, although the idea of identifying Geminga with a Vela-type pulsar appears, somewhat by default or because of the lack of a better candidate, to be the most immediate solution, several difficulties are presented by this identification, some (but not all) of which could be eased by considering an "older" pulsar. A peculiar, if not unique, object cannot be excluded considering that the distance estimate given above could also be too generous and that nothing in the data prevents the source from being even much nearer. A more general difficulty, of course, is that of attaching the label "pulsar" to an object for which no time variability of any find, at any wavelength, is seen.

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