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THE ILLUSIVE GEMINGA: WHAT IS IT?

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ABSTRACT

The first unassociated gamma-ray source was discovered by SAS-2 in 1973 (Kniffen, et al., 1975) and later confirmed by COS-B (Bennett, et al., 1977). Following the announcement, there were numerous attempts to find a counterpart, and many models were developed to explain the source. Now over fifteen years later this illusive source still remains as one of the major riddles of astrophysics. Why is an object, which is able to emit such energetic photons, so well concealed at other wavelengths? The association with the *Einstein* source 1E 0630+178 is the most favored (Bignami, Caraveo, and Lamb, 1983), but this cannot be considered proven. The pulsar emission model of Ruderman and Cheng (1988) is appealing in its broad applicability, but awaits observational confirmation. The EGRET instrument on the Gamma-Ray Observatory will provide a major improvement in observational capability to better define the location and spectrum of this source, and hopefully will lead to a confident identification.

I. INTRODUCTION

Among the first gamma-ray sources detected by SAS-2, superseded only by the Crab Nebula and Vela radio pulsars was an unidentified source in the Galactic anti-center region at l=195, b=+5. Later confirmed by the COS-B collaboration, this source is listed in their second catalog as 2CG195+04. It is the second most intense source above 100 MeV, next to the Vela pulsar, and has the hardest spectrum of any source for which one is obtained. Although the lack of unique signatures such as contemporary time fluctuations has not allowed a definitive identification of Geminga (See Bignami, Caraveo, and Lamb, 1983, for the origin of this alias.), the latter reference claims identification with an Einstein source 1E 0630+178 and Moffat et al. (1983) possibly with a Z=1.2 Quasar. The outer gap model of Ruderman and Cheng (1988) seems to fit the observations well and would favor a galactic pulsar model. The wide beam predicted by this model might account for many hard spectra gamma-ray sources, not identified as radio pulsars, where a narrower beam is expected.

II. OBSERVATIONAL HISTORY

The first discovery of a gamma-ray discrete source not associated with a known object was reported by the SAS-2 group (Kniffen et al., 1975). A contour plot of the galactic anti-center region for gamma-rays above 35 MeV (Figure 1) showed a clear excess at l=195, b=+5. This result was confirmed by the COS-B Collaboration (Bennett, et al., 1977) who reported a position of l=196, b=+4. In the second COS-B catalog (Swanenburg, et al.,

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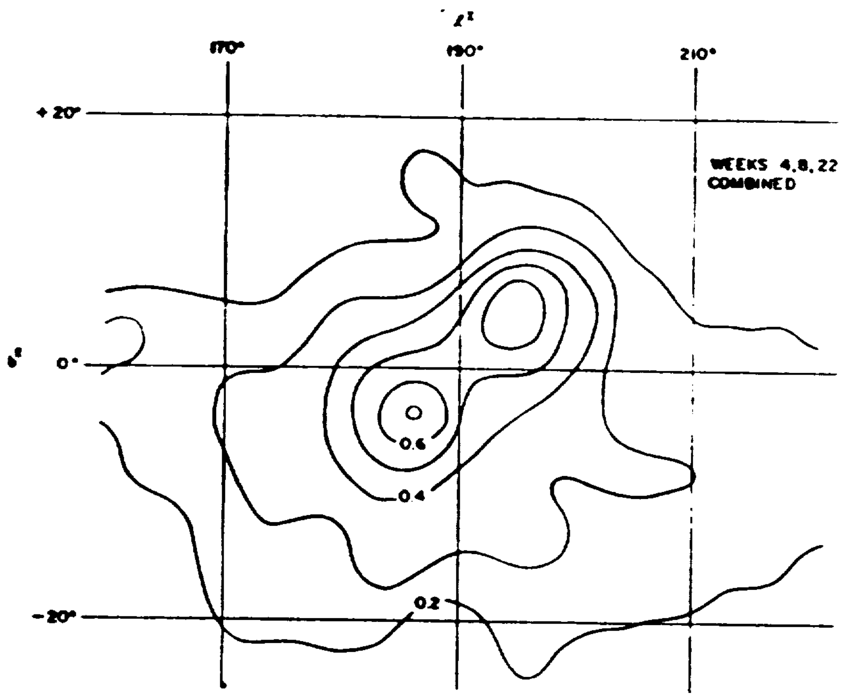

Fig. 1. Contour plot from the original discovery of γ195+5 Kniffen, et al., 1975). This plot refers to gamma-rays above 35 MeV.

1981), the location of 2CG195+04 is given as l=195.1, b=+4.5. An error radius of 0.4 degrees, although statistically precise, may still contain systematic errors resulting from the very complicated structure of the diffuse or unresolved discrete source emission in this region. Geminga is the second most significant source listed in the 2CG catalog, the Vela pulsar being the most significant. The flux above 100 MeV given in the 2CG catalog is 4.8×10^{-6} ph $cm^{-2}s^{-1}$ in agreement with the SAS-2 flux (>100 MeV) of $(4.3 \pm 0.9) \times 10^{-6}$ $cm^{-2}s^{-1}$ (Thompson, et al., 1977).

Although both SAS-2 (Thompson, et al.,1977) and COS-B (Swanenburg, et al.,1981) indicate a hard spectrum for Geminga, the only published spectrum is given by Hermsen (1980) and is reproduced in Figure 2. Not only is the spectrum the hardest of any source for which a spectrum was obtained, it appears to bend over below 100 MeV. Despite many observational attempts, no gamma-ray detections below 100 MeV have been reported (Haymes, Meegan and Fishman, 1979; Graser and Schönfelder, 1982).

Reports of a weak indication of a 59 second periodicity in the flux seen by SAS-2 (Thompson, et al. 1977) were confirmed by COS-B (Masnou, et al., 1977) and also evidence for x-ray periodicity in the *Einstein* and EXOSAT data was reported by Bignami, Caraveo and Paul (1984). A later analysis (Buccheri, et al., 1985) questioned the significance of these claims. Confirmation with the high sensitivity of EGRET should be awaited before these results are taken seriously in modeling the gamma-ray emission from 2CG195+04.

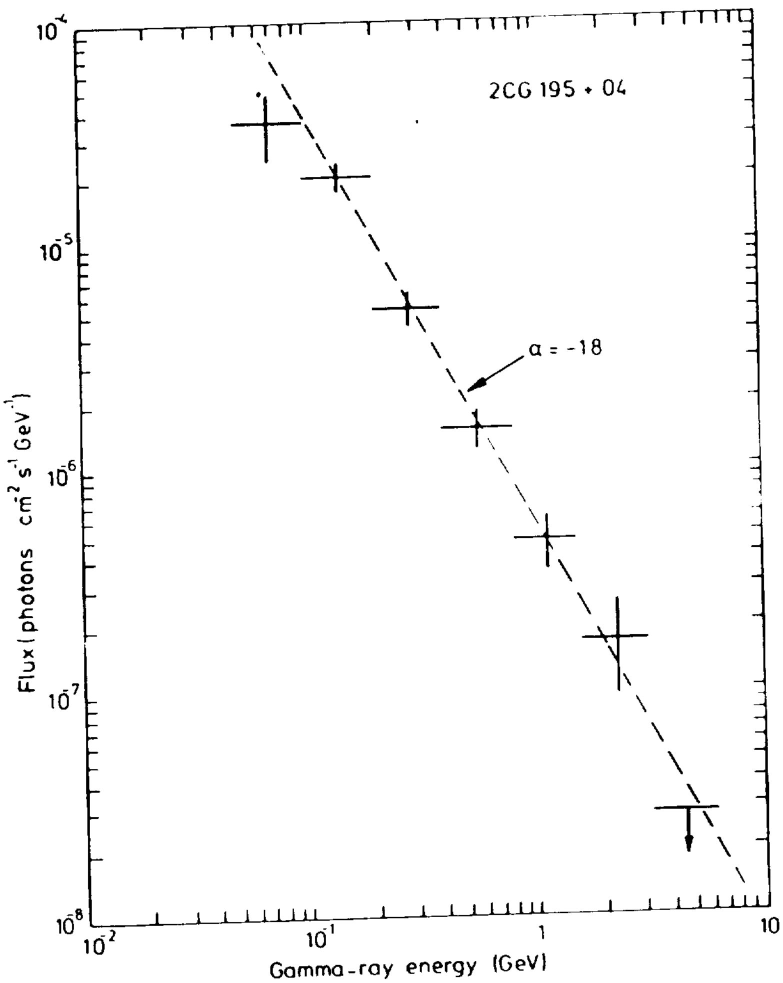

Fig. 2. Differential energy spectrum of the Source 2CG195+04 observed by COS-B (Hermsen, 1980). The dashed line is a power law fit to the data points.

III. THE SEARCH FOR COUNTERPARTS

Following the discovery of Geminga, extensive searches of existing catalogs (Cesarsky, Cassè, and Paul, 1976; Bignami, Macccacaro, and Paizas, 1976; Thompson, et al., 1977) showed no candidates at other wavelengths based on the lack of positional coincidences.

The first claim of an association resulted from a HEAO-A2 observation of a weak x-ray source for which the HEAO-1 and COS-B error boxes overlapped (Lamb and Worral, 1979). However, the significance of the positional coincidence was not strong and no other compelling characteristic of the x-ray source supports the identification.

Einstein IPC observations of the region provided four candidate x-ray sources (Bignami, Caraveo and Lamb, 1983). The Einstein source, 1E 0630+178 the strongest of these four weak sources, was found to have a soft spectrum, display no absorption feature, and to have a spatial extent consistent with the instrument point spread function. Lack of a VLA detection at 6 cm or optical sources in the error box implies an unusually high x-ray to optical luminosity ratio. These unique features led Bignami, Caraveo and Lamb to claim an association. Subsequently Caraveo, et al. (1984) proposed a 21st magnitude blue star as the optical counterpart, but Halpern, Grindlay and Tyler (1985) argued against this association.

A deeper optical search by Bignami, et al. (1987) revealed two sources having r magnitudes ~24.5 and ~25.5, and suggested the fainter as a candidate for association based on its bluer spectrum. Using the Hale 5m telescope with three color CCD photometry, Halpern and Tytler (1988) find this object to be the bluest, by far, in the field, and argue it could be a very compact synchrotron source.

An alternative association has been suggested by Moffat, et al. (1983). These authors identify the best candidate radio source from a survey of the COS-B error box by Sieber and Schlickeiser (1982) with a 19th magnitude z=1.2 quasar, QSO 0630+180. The radio source has the flattest radio spectrum in the region and is the only one with a clear optical counterpart. The quasar association implies a gamma-ray luminosity of about 10^{48} ergs s^{-1}.

A search of the Geminga error box at 21 cm by Spoelstra and Hermsen(1984) revealed over 15 sources between ~4 and 50 mJy. None were deemed by the authors to have sufficiently anomalous properties to be considered viable candidates for association with the gamma-ray object.

IV. INTERPRETATION

The current situation with regard to the identification of the source, originally given the name γ195+5 (Kniffen, et al., 1975), is still far from resolved. The possibility that it is a quasar cannot be ruled out since 3C273 appears to be well established as a gamma-ray source (Bignami, et al., 1981), and the quasar 0241+622 is a candidate for 2CG135+01 (Apparao, et al., 1978). The gamma-ray luminosity of ~10^{48} ergs s^{-1} deduced if the association with QSO 0630 +180 is correct is ~10^2 times that deduced for 3C273!

Assuming the association with 1E 0630+178 and the apparently association with a faint blue counterpart is correct, the characteristics which must be explained include luminosity ratios

L_γ/L_X~1000, L_X/L_{opt}~1800, the lack of an extended x-ray synchrotron nebula, and a soft x-ray spectrum. As discussed by Halpern (1989), the only known objects with such a high L_X/L_{opt} ratio are neutron star binaries with low-mass companions, and some radio pulsars or other compact objects related to supernova remnants. The large L_C/L_X ratio is consistent with a pulsar, where the gamma-rays are produced far from the surface to avoid degradation of the spectrum by self absorption and reprocessing. Since the emission cone would be larger near the speed of light cylinder than at the polar cap (Cheng and Ruderman, 1980), it is reasonable that the pulsed emission would be seen at gamma-ray energies, but not in the radio. Unfortunately, statistical limitations prevent a period search in the gamma-ray observations.

The most comprehensive model for explaining Geminga as a pulsar is given by Ruderman and Cheng (1988). They note the similarities with Vela in the luminosity ratios, and that Vela, unlike Geminga has an extended x-ray nebula. They argue this is consistent with their model of pulsar spectral evolution in which the x-ray luminosity of a Vela like pulsar becomes increasingly small compared to the gamma-ray luminosity. The source mechanism for the gamma-rays from such objects is synchrotron emission by $e^{\pm}$ pairs created in the neutron star's outer magnetosphere. Geminga would be a further evolution of a Vela like pulsar in this scenario in which the magnetic pole has become nearly aligned with the spin axis. One consequence of the near alignment is a smaller x-ray synchrotron nebula. Another is that the modulation of any gamma-ray emission at the pulsar rotation period would be small, and difficult to detect. Ruderman and Cheng (1988) present plausible arguments that the 20 unidentified sources in the COS-B 2CG catalog could be a manifestation of pulsars in this stage. The final stage of the evolution of such objects is reflected as hard spectra gamma-ray burst sources.

Other models have been proposed to explain the observed properties of Geminga (Maraschi and Treves, 1977; Langer and Rappaport, 1982; Nulsen and Fabian, 1984; Bisnovatyi-Kogan, 1985) but recent work has left them in less favor and they will not be discussed here.

V. PROSPECTS FOR IDENTIFYING GEMINGA

None of the associations with Geminga which have been described above are definitive. The probability of finding an *Einstein* HRI source in the COS-B error box is about 5 percent (Halpern, Grindlay, and Tytler, 1985). The optical association with a faint blue object adds to the case, but cannot be considered entirely decisive. The case for the radio-bright quasar is even less convincing with about a 20 percent chance probability (Moffat, et al., 1983). A more confident association will await the improved observations with HST, ROSAT, AXAF and GRO. In all cases there will be remarkable improvements in sensitivity and resolution. With GRO/EGRET, the observations will not only be vastly more sensitive and with better precision in both position and energy, but the spectrum will be measured up to 20 GeV or more, where the position can be determined even more accurately. Thus the prospects for understanding the "Illusive Geminga" appear very good. Furthermore, the expanded catalog of sources which the great leap in sensitivity will provide, will shed new light on the interesting possibility that "radio quiet" pulsars are a major explanation for the unidentified gamma-ray sources.

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