VI. OTHER MANIFESTATIONS OF NEUTRON STARS AND THEIR PLACE IN NEUTRON STAR EVOLUTION

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Neutron Stars and Gamma-Rays

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1. Introduction.

Neutron stars are difficult to observe. This has always been known, since the time of their conception back in 1932, just after the laboratory discovery of the neutron, and also since the time of the first pulsar observation in 1968. And yet they must be abundant in our Galaxy, if they are a frequent endpoint of stellar evolution: may be as many as 10^{9}, if they have been appearing at the rate of $\sim 10^{-1}$/year over a Hubble time. This, for any reasonable disc distribution, implies that the nearest to us is only ~ 10 pc away, and, what's more, that there could be $\lesssim 1{,}000$ within 100 pc from us. There also seems to be a reasonable consensus (see Manchester, 1987; and Naranyan 1987) that the total number of pulsars in the Galaxy, i.e. of those neutron stars that are currently in the active pulsar phase, is 1-3 x 10^{5}, and that of these some 5-7 x 10^{4} should be observable with an "infinite sensitivity" telescope. The current grand total of radio pulsars detected in our Galaxy is 435 (Manchester, 1987), and to these observations we owe much of what we know about neutron stars. Gamma rays, however, are also coming up strong as an observational channel for neutron stars, and one that is unique in its width: it covers nearly ten decades of photon energy (from 10^{6} to 10^{16} eV), and as such it also probably covers a rich variety of physical processes happening on and near the neutron stars. The total number of objects observed in gamma-rays, and surely or most probably associated with neutron stars is similar to that of the observed radio pulsars, featuring:

- -400 gamma-ray "busters", probably associated with a local population of binary neutron stars undergoing weak accretion from underluminous companions.
- -two fast radiopulsar (in Crab and Vela), several (~ 5) X-ray binaries, including the "honorary" binary Cyg X-3 and the "exotic" one SS433.
- -an unkown fraction of the 20 Cos-B Unidentified Gamma Objects in the galactic plane, including Geminga.

While an extensive presentation of both the gamma-ray burst phenomenology and of Cyg X-3 are given elsewhere in this volume (see

D. J. Helfand and J.-H. Huang (eds.), The Origin and Evolution of Neutron Stars, 465–475.

Hurley, 1987 and Barnard, 1987, respectively),in what follows we shall briefly review the highlights of the gamma-ray manifestation of the Crab and Vela pulsars, present a summary of the evidence of UHE/VHE (10^{11}-10^{16}eV) emission from X-ray binaries, give the latest Cos-B Collaboration results on high-energy ($\gtrsim$100 Mev) galactic sources, and finally present an update on the work in progress toward the identification of Geminga, our best case for nailing an UGO. Much more detailed work on the energetic emission on neutron stars, both from an observational and interpretative viewpoint, can be found in the recent review by Ruderman (1986).

2. Highlights of recent gamma-ray observations of the Crab and Vela pulsars.

The gamma-ray emission from the two fast radiopulsars in Crab and Vela (PSR 0531+21 and PSR 0833-45) has been investigated for about one and half decade now, with a wealth of data summarized e.g. in Bignami and Hermsen (1983), and more recently, in Ruderman (1986). Briefly, the data now consist of:

-strong, pulsed emission in the 10^{6}-10^{9} eV region, studied in detail in balloon and satellite missions.

This gamma-ray emission is important for the overall energy budget of the neutron stars, being, in the case of the Crab, $10^{-4}$of the total e.m. pulsar energy loss, and as such only slightly inferior to the energy channeled in pulsed X-rays. In fact, up to the upper limit of the Cos-B energy range, and starting from the hard X-ray region, PSR 0531+21 shows a remarkably constant power-law spectrum with $dN/dE \sim E^{-2}$, i.e. with a costant energy content per decade. In this context, the only new information is that on detailed spectrum from the Crab pulsar in the final Cos-B data base.

Fig 1, taken from Clear et al (1986), shows the pulsed gamma-ray emission of PSR 0531+21 in several energy intervals over the Cos-B range and for the totality of the data of the $\lesssim$ 7-year mission. Possible variability of emission has also been observed by Cos-B, albeit at the $\sim$99% confidence level (Wills et al, 1982).

-VHE (10^{11} eV) gamma-ray have been observed from the Crab (e.g. Dowthwaite et al, 1984), and, with a smaller degree of confidence also from the Vela pulsar .

Here the overall energy involved is somewhat smaller, 10^{-2} of that at e.g., 10^{8}eV, and the overall spectrum does indeed show a steepening.

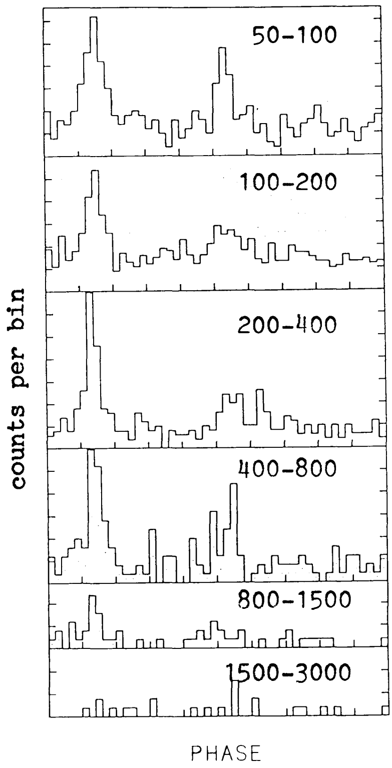
-Finally, there have been recent reports of UHE ($\gtrsim 10^{15}$ eV) gamma-rays observed from the Crab Nebula region, with no evidence as yet of pulsed emission.

If confirmed (see e.g. Dzikowsky et al.1981, Kirov et al. 1985), this all-important observation would imply the presence at or around the pulsar of particles with energies in excess of 10^{15}-10^{16} eV.

Obviously, young, rapidly spinning neutron stars like Crab and Vela can act as potent accelerators, in the sense that for them the Ω^2B term can sustain the strong potential drops ΔV's eventually responsible for the particle acceleration. However, the VHE/UHE observations have

Fig.1

Phase histogram of the total gamma-ray emission of PSR 0531+21 in six energy intervals.
Interval boundaries are given.



implications on the acceleration sites and / or mechanisms: photons of $\sim 10^{15}$ eV cannot escape from the intense magnetic field regions around the neutron stars, and need to be originated at distances comparable to that of the light cylinder radius ($\sim c\Omega^{-1}$) in order not to be absorbed by the pair production in the strong B .This becomes even more stringent if the 10^{15} eV emission form the Crab is shown to be pulsed.

3. Gamma-Rays from X-ray Binaries

One of the greatest results of ground-based gamma-ray astronomy in recent years has been the detection of very energetic emission from a number of binary systems containing a neutron star undergoing strong accretion from the non-collapsed companion. As such, these systems have all been well studied through X-ray astronomy, and it's mostly through their X-ray signatures that the gamma-ray identifications have been possible. Table 1 of Rudermann (1986)gives a summary of the results reported so far for the VHE and UHE observations; while it is very difficult to assess accurately the confidence level of the various results, based generally on limited statistics, it is hard to see how they could all be wrong, especially for the cases were several independent confirmations now exist. Critical rewiews of the recent results are available, but especially for Cyg X-3, the 'honorary' X-ray binary, the VHE/UHE evidence is now overwhelming, and confirms the brillant observations of the Crimean group (e.g. Stepanian et al.1977), who have been claiming observations of this source for well over a decade. The energetic emission of these systems, in general terms, must be linked to the presence of a rotating neutron star, but by no means to it alone. Indeed, neutron stars in these X-ray binaries are relatively old and are all slow rotators, so that their $\Omega^2 B$ is certainly not capable of producing the necessary ΔV for acceleration. For the specific case of Cyg X-3 many models exist and are discussed by Barnard (1986). In general, two basic approaches have been so far proposed for the creation of UHE/VHE gamma-ray in neutron-stars X-ray binaries. They have in common, as mentioned for the case of radiopulsars, the need for producing the energetic gamma-ray far enough from the intense neutron stars magnetic field; this can be accomplished either by creating the accelerating conditions in regions where $B \lesssim 10^3$ G (the limiting field for $\gtrsim 10^{15}$ eV gamma's), or by extracting energy from high-B regions in the form of nuclear beams, made to interact subsequently to yield electromagnetic by-products where they have a chance to escape. One way of producing the required ΔV for particle (proton) acceleration is to have charged matter moving at high speed in strong magnetic field: this (Chanmungam and Brecher, 1985) is accomplished near the pulsar magnetosphere at the inner edge the accretion disc, if this is available in the system. Note that the B at the magnetospheric radius is in general much higher than the value (10^3 G) required for escape - so also in this case energy trasport in the form of proton beam up to the production region is substantially required. The other proposed accelerator mechanism (e.g. Vestrand and Eichler, 1982) is in the accretion shock generated by infalling matter near (e.g. $\lesssim$ 1 stellar radius away) the neutron star surface. One needs to put the accelerator near the neutron star surface if the 10^{15}-10^{16} eV luminosity is to be directly accretion powered because it represents a big (10%) fraction of the overall accretion luminosity $GM\dot{M}R^{-1}$. Some difficulty arises then with electron synchrotron losses in the standard high magnetic fields expected ($\gtrsim 10^8$ G), so that a lower surface magnetic field neutron star may be helpful in this picture.

4. Cos-B Sources vs. Unidentified Gamma Objects.

The picture of the $\gtrsim$100 mev gamma-ray sources in the Galaxy, as proposed by the Cos-B mission (Swanenburg et al, 18981), and further discussed by Bignami and Hermsem (1983), has recently undergone some serious changes (see, e.g. Pollock et al, 1985a). This is due to a re-analysis of the complete Cos-B data set in the light of new radio-astronomical information bearing on the gaseous content of the galactic disc. In particular, the recent mapping in the CO mm. line of low-latitude regions has permitted to evaluate the content of H2, an abundant but elusive state of galactic hydrogen, and one with a quite different distribution than that of the 21 cm. line data tracking the HI. The latter represented, until recently, the only known ISM on which to let the galactic CR interact to produce the flux of diffuse galactic radiation. It was against such diffuse radiation, taken as a background, that the Cos-B sources were found as significant excesses, unresolved by the instrument's PSF. Clearly, the detection of more gas, and all at very low galactic latitude, has changed the situation, and several excesses in the 2CG catalogue can now be well explained by interaction with the ISM of CR taken to have a local spectrum. Accordingly, these 2CG objects are to be dropped from a list of sources proper, but, on the other hand, also a few other true sources now appear which had not been seen before. Table 1 of Pollock et al. (1985b) summarizes the situation, showing which 2CG objects have fallen below the required significance and which new ones have popped up; however, the work has only been done so far for those parts of the galactic disc covered by the CO surveys. More work is in progress, leading eventually to a complete new list of true galactic sources; meanwhile, it would be premature to speculate on what their final number will be and on how different will this be from the current $\sim$ 20 or so.

The general characteristics of the bona fide sources are:

- $L \simeq 10^{36}$ erg/sec
- $\langle E_{\gamma} \rangle \sim 250$ Mev
- in some cases, at least, time variability

and it is therefore logical to associate them with compact objects, e.g. with some manifestation of neutron stars. They remain, however, UGO's. They are not associated with those more obvious neutron star symptoms observable at other wavelengths: they are not bright X-ray binaries (or bright X-ray sources at all), nor radio pulsars. And yet, of course, such symptoms are available only for a tiny fraction ($\sim 10^{-6}$) of all the neutron stars in our Galaxy, so that one should really not be too surprised if, with gamma-ray astronomy, we may have stumbled onto a new manifestation or a different physical scenario. It is nevertheless the observer's duty to search for accurate identifications so that, in parallel with radio searches, it was also resorted to X-ray searches (see, e.g. Caraveo, 1983). As a result of the exploration with the Einstein Observatory of several Cos-B error boxes, many new X-ray sources were discovered, and a subsequent program of optical identification and understanding was initiated. Many of the new sources have now been identified and are accounted for in terms of known objects, and as such with no special reason for being responsible for gamma-ray emission. A few, however, are still unidentified, and as such remain potential candidates. Of these, unfortunately so far only one case could be studied in detail, that of Geminga. For the others, still pending , the high resolution instruments on Eistein or EXOSAT did not make it to supply us with good enough positioning to start optical identification work.

5. Work in Progress on Geminga.

As a result of the X-ray exploration of the 2CG195+4 (Geminga), Bignami Caraveo and Lamb (1983) reported the discovery of 4 new IPC sources very near to or within the half square degree Cos-B error box. Of these, two were immediately identified with a field star and an external radio galaxy, while a third, 1E0630+18, has been only recently identified through an EXOSAT CMA 10" positioning (Bignami et al, 1985.). The fourth, 1E0630+178, and by far the brightst source ($\sim 2\times10^{-12}$ ergs/cm^2 sec in the IPC range), remains the toughest candidate for optical identification, but is the best candidate for the gamma-ray source and is, in any case, most likely associated with a compact object, probably a neutron star. This is the first case of an object, discovered through its gamma-ray emission, being tracked down to x-ray and optical wavelengths; not altogether unexpectedly, it's turning out to be quite different from other known manifestations of neutron stars. In order to better understand this, a short summary of very recent work follows, in fact anticipating forthcoming complete presentations of results.

After the surprising result of the periodicity evidence in the Einstein 1979, 1981 and EXOSAT 1983 X-ray data of 1E0630+178 (Bignami, Caraveo ,Paul, 1984), a new long (64,000 secs) EXOSAT observation was performed in 1985, yielding about 1200 source photons. Their arrival times were periodicity-analyzed in the interval from P= 60.20 sec to P= 60.35 sec., i.e. in that interval obtained from the extrapolation to the measurement date of the previous three periodicity measurements, implying a high $\dot{P}\sim 4\times10^{-9}$ sec/sec. A very significant positive result at 60.28 secs was found in this small interval, covered in 30 independent steps of 5×10^{-3} secs each . A posteriori, a wide scan was performed (from 10 to 110 secs in period), to check on the presence of other, possibly spurious, signals. No other signal of comparable significance was found, except for the harmonics at exactly 1/2 and 1/4 of the 60.28 secs signal. Fig 2 shows the "secular" X-ray period change plot. As mentioned, a more detailed presentation of these data is currently being prepared, including a study of the possible time-variability of the periodicity effect within the 64,000 secs observation.

As to the problem of the optical identification of 1E0630+178, a first proposal had been made by Caraveo et al (1984) and Sol et al (1985) for an $m_V\sim 21$ object, located at the edge of the HRI error box, at 4.2" from its centre. This object was then subject to spectral and time variability studies (e.g. Halpern et al, 1985 Kulkarni and Djorgovski, 1986), which, although difficult because of its faintness, did not reveal any peculiarity, all data being consistent with a G type field star. This fact, coupled with the marginal positional coincidence, cast some doubt on the proposed identification; however, only recently the final word has been said by IR data on this object, kindly taken for us by M.Lebofski at the MMT. The observed K and J magnitues allow finally to join with a smooth Plankian curve all the optical-IR data; the resulting best fit yields a temperature of 5500°K (consistent with the scant continuum spectral observations) but requires an IS absorption Av $\gtrsim$ 1 mag. This is clearly incompatible with the X-ray deduced NH ($<10^{20}$ cm^{-2}), and it thus represents a strong, and probably final, argument against this object being associated with the X-ray source. The optical observations have yielded at least one and possibly two other objects in the HRI error circle (of $\sim$ 50 sq. arc secs), but of such faint magnitudes (24.5 and 25.5), that their probability of chance presence is very high (see e.g. Djorgovski and Kulkarni,1986 and Bignami, 1986). Early reports of possible proper motion of either of the

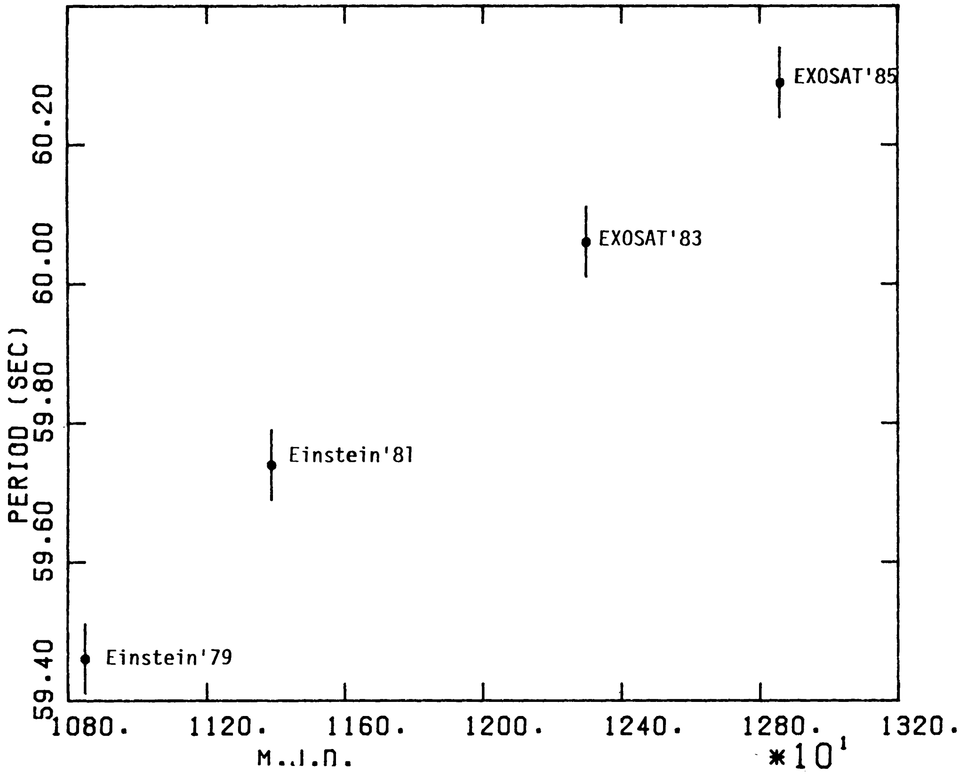


Fig 2
Time history of the 59/60 sec periodicity.

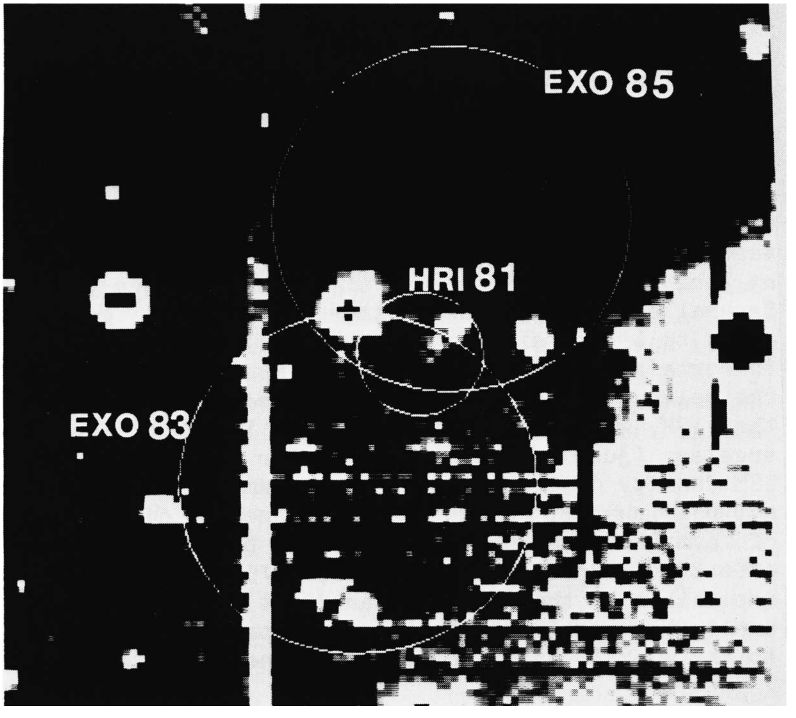


Fig 3
Stack of 12 CCD plates of 15 m each taken at the CFHT in January '84 (N at bottom E at left).

two faint objects still await confirmation, but may have to wait until the Space Telescope becomes operational. Fig. 3 is a stack of many CCD exposure taken at the 3.6 CFHT telescope. The HRI error box has the 'old' mv 21 candidate at the SE edge, and the other faint objects inside. The EXOSAT error boxes of 1983 and 1985 are also shown.

What do the data gathered so far on Geminga/1E0630+178 and its possible optical counterpart tell us ?

- The 50 Mev-few Gev gamma-ray flux is $\sim 2\times10^{-9}$ erg/cm^{2}sec, or 1,000 higher than the ~Kev X-ray flux
- In turn, Fx/Fv $>$ 1,000 or 2,000, or 3,000, depending whether the counterpart is either or none of the two faint objects in the HRI box.
- The IPC spectrum is soft, well consistent, e.g. with a BB spectrum with $T\sim 9\times10^5$ °K; the observed NH, certainly less than 10^{20} cm^{-2}, and consistent with zero, places the source nearer than 100-200 pc. Support to this comes from remembering the NH=3×10^{21} cm^{-2} to the Crab, located at 2 Kpc in a similar l, b position, and from the Nh 2×10^{20} cm^{-2} to the galactic pole, i.e. through $\sim$ 200 pc of decreasing density disc.
- The source periodicity (and its $\dot{P}$), now apparently confirmed for the X-ray data, but no longer seen (possibly owing to instrumental limitations) in the gamma-ray data (see Buccheri et al, 1985).
- Deep radio searches have not revealed the existance of a pulsar or of any radio source compatible with HRI position.

As already pointed out by several authors, this sum of evidence represents a unique set of properties, not found so far in astronomy, even independently of the gamma-ray emission. It is tempting to try to interprete this set of properties with a model involving a neutron star - even if a model based on, e.g., a black hole does exist (Bisnovathi - Kogan, 1985). The simplest would be, for the X-ray and optical data at least, that of thermal emission from an isolated neutron star (presently non active as radio pulsar) at a distance of less then several tens of parsecs, within which hundreds of such objects should exist. At 40 pc, for example, the observed X-ray flux is explained with a surface of $\lesssim 10^{10}$ cm^2 at the observed temperature of 9×10^5 °K, possibly the heated polar cap of a neutron star . The optical emission around mv 25 would then be accounted for by thermal emission of the rest of the neutronstar surface at the same distance and at a much lower temperature ($\gtrsim$50,000 °K). Several questions arise: can such a thermal gradient exist? According, e.g., to Greenstein and Hartke (1983) it could be not impossible, but it is certainly difficult to be more precise. More importantly, what heats the polar cap? In an isolated neutron star, it could be accretion from the ISM, which, in a scenario à la Bondi, could provide Lx 10^{29}-10^{30} ergs/sec (just the right amount) for space velocities of 100 Km/sec and ISM density of 1 cm^{-3}, i.e. for parameter values slightly favourable but not unthinkable. However, a fundamental difficulty with ISM accretion of a magnetized neutron star is posed by the so called "propeller effect" (Illarionov and Sunyaev, 1975). The case for IS accretion being impossible on the neutron star if it retains a magnetic field is in fact explicitly treated in that seminal paper, where it is shown that, owing to the weak IS mass transfer, the neutron star would have to slow down

to periods so long as could only be achieved in more than a Hubble time. Alternatively, it can also be shown that, even for $P \sim 100$ secs, the gravitational capture radius (equivalent to the magnetospheric radius if the B field is confined by ISM pressure) is much greater than the corotation radius, and thus no accretion can take place. If the ISM accretion, invoked to heat the polar cap, is not viable, the simple model of thermal emissions from a slowly rotating neutron star is also untenable (which is just as well, because it would have been very difficult to explain at least 10^{33} ergs/sec of gamma-rays from it).
Some form of non-thermal emission can certainly be postulated (e.g. Katz, 1985), but it would seem more natural to turn one's attention to binary systems, obviously with an underluminous companion to a collapsed object. The case for two neutron stars has been considered by Nulsen and Fabian (1984), and that of a black hole/white dwarf system by Bisnovathi-Kogan (1984), (based on the "old" optical identification). Certainly, a binary model would also have the advantage of greater latitude for explaining the gamma-ray emission and the (period)/(period derivative) combination, unique for this object. Another qualitative consideration against Geminga-like objects being too common (as, e.g., old isolated neutron stars) is that if their gamma-ray luminosity is at least 10^{33} ergs/sec (that for a Geminga distance $\sim$ 100 pc), their current total number cannot exceed 10^5-10^6 (but could also be much less), or their summed gamma-ray emission would exceed that of the total Galaxy of $< 10^{39}$ ergs/sec. Such maximum number $\sim 10^{-3}$ of the total galactic neutron stars could indeed point to a relatively rare neutron star binary combination, exceedingly luminous in gamma-rays, of which current gamma-ray astronomy has detected the nearest specimen; note that Geminga would not have been seen by SAS-2 or Cos-B if it were only a factor of ~ 3 further away, owing to the current sensitivity limitations.This helps in explaining its apparent uniqueness. On the other hand, as mentioned above, sources with similar gamma/X/optical combinations could be buried in the existing data, which are very limited in sensitivity and angular resolution.

It is perhaps appropriate to close by remarking that the type of astrophysical scenario described above is strikingly reminiscent of those imagined for gamma-ray bursters; even if Geminga has never been seen to burst in gamma-rays, it is true that a similar "steady" high-energy gamma-ray luminosity would still be undetectable for the vast majority of the gamma-ray burst population. No optical flashes are visible at the Geminga position in the Harvard plate collection (that was checked ,Bignami et al.1983) , and no convincing steady-state X-ray source has been associated with bursters, and so the similarity remains a speculation - still it provides a clear indication for future observational work.

It is a pleasure to thank J. Arons for enlightening discussions and D. Helfand for stimulating scientific conversations some of which were held in China's remote and beautiful corners.

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DISCUSSION

J. Grindlay: What constraints, if any, can be placed on variability of the 100 MeV emission from Geminga. Do the Cos-B vs. SAS-2 data suggest long-term variability? Is there any indication of changes in spectra in the Cos-B data?

G. Bignami: No evidence of long term flux and/or spectral variability from Geminga is visible in the Cos-B data base. However, the rather large (say 20%) error margin within which data from the 7 year mission can be compared does not allow for a very strict statement on this.

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G. Frontera: What do you think of the proposal by Chinese astronomers to identify Geminga with a SNR, with explosion recorded in ancient records?

G. Bignami: As you can clearly see from the enclosed figure, the record only speaks of a guest star as big as an orange, i.e., not of the more classical "melon" size associable with SN explosion and moreover shining for only a short time. As to the positional coincidence, the recorded error box is even bigger than that of Cos-B. Finally, let me underline that this proposal was first made by Vladimirskii as mentioned in Bignami <u>et al.</u> 1984.

魏太延三年正月壬午，有星
晡前昏见东北，在井左右，
色黄，大如桔

魏收 572年 魏书 105卷

元嘉十四年正月，有星晡前
昏见东北维，在井左右，
黄赤色，大如桔

J. Dolan: With regard to the optical counterpart of 1E0630+178, what type of UV spectrum would the various models you discussed predict?

G. Bignami: The (otherwise untenable) single neutron star model would predict a strong UV flux relative to the optical, if we are looking at an object with surface temperature $\gtrsim 10^4$ K. In any binary model it is not completely clear where the optical light would be coming from, but my guess is that it would also have a strong UV component. We have looked at Geminga with IUE, of course, without success, but we have great hopes in the ST.