Geminga and the Astronomy of Isolated Neutron Stars

Giovanni F. Bignami

A neutron star forms by the collapse of a massive star that has exhausted its nuclear fuel so that energy from thermonuclear reactions can no longer sustain the star against the compression of its own gravity. The resulting high density object (1.4 solar masses packed into a sphere of a 10-km radius) is just one stop short of the irreversible catastrophe that generates black holes. Ordinary matter is compressed in a neutron "fluid" state. Neutron stars are by definition difficult to detect; any atmosphere they might have is confined to a scale height of a few centimeters, so they do not radiate like ordinary stars. But they possess other remarkable properties, such as magnetic fields in the region of 10^{12} G, electric fields of order gigavolts per meter and higher, temperatures as high as 10^9 K, and, in general, a reservoir of rotational kinetic energy output that can be significantly greater than the total luminosity of our sun. With these properties in mind, it is not surprising that electromagnetic energy emitted by neutron stars tends to come out in the high-energy domain. One set of recent results, in fact, points to gamma rays as the channel where most of the neutron star emission arises.

The gamma ray power of isolated neutron stars was first recognized by the National Aeronautics and Space Administration's (NASA's) second Small Astronomy Satellite (SAS-2, launched in November 1972), which had a payload dedicated to gamma ray astronomy. Among the notable results of this mission was the discovery of three gamma ray "sources," measurable localized flux enhancements. Two were identified (because of their pulsations) with the Crab and Vela pulsars, at the time the two youngest neutron stars, but the third source, toward the galactic anticenter, could not immediately be identified with any known object at other wavelengths.

Further progress came in 1975 with the European Space Agency's COS-B gamma ray mission, similar to SAS-2 in detection capability but lasting 7 years against about 7 months for SAS-2. The two pulsars and the unidentified source were observed in long and repeated exposures, yielding photon statistics about 10 times better than that of SAS-2 and allowing for more accurate source locations, down to a circular "error box" of about 0.5° in radius. Although extremely poor by the standards of optical or radio astronomy, these error boxes were good enough to permit meaningful counterpart searches. In 1978, NASA launched its second High Energy Astrophysical Observatory (HEAO-2), renamed the Einstein Observatory, which offered, for the first time, a grazing-incidence optics system that was able to focus x-rays down to a few arc seconds over a field of view of up to 1°. A program was started to search the error boxes of several SAS-2–COS-B gamma ray sources for possibly unusual x-ray objects, and one of the targets was the still mysterious galactic anticenter source, which had in the meantime acquired the name Geminga, for a GAmma ray source in the constellation GEMINi. The acronym is really based on a pun in Milanese dialect: "Gh'e' minga" means "it's not there" or "it does not exist," reflecting the difficulties that some of us in Milan were having with this celestial object. The name stuck and did much for the furthering, if not of high-energy astrophysics, of the noble Milanese argot.

Einstein observations in 1979 and 1981 found a bright x-ray source, dubbed 1E0630+178 from its celestial coordinates (Fig. 1), in the Geminga error box. This was the brightest x-ray source in the region and the only one not immediately identifiable with known celestial objects, such as normal stars or galaxies. In fact, out of all other equivalent sources in the Einstein Observatory catalog, 1E0630+178 alone did not show an optical counterpart down to the limiting magnitude of the Palomar Observatory Sky Survey plates. This was very reminiscent of the case of the Vela pulsar, which is a bright gamma ray source, an x-ray source with flux comparable to 1E0630+178, but a very faint (23rd magnitude) optical object. Geminga, it was reasoned, could also be a relatively local neutron star, but there was one important difference: The Vela pulsar is a strong radio object, PSR 0833-45, whereas Geminga does not show, even now, any sign of radio emission, even after deep, extended searches with the great Arecibo radio observatory.

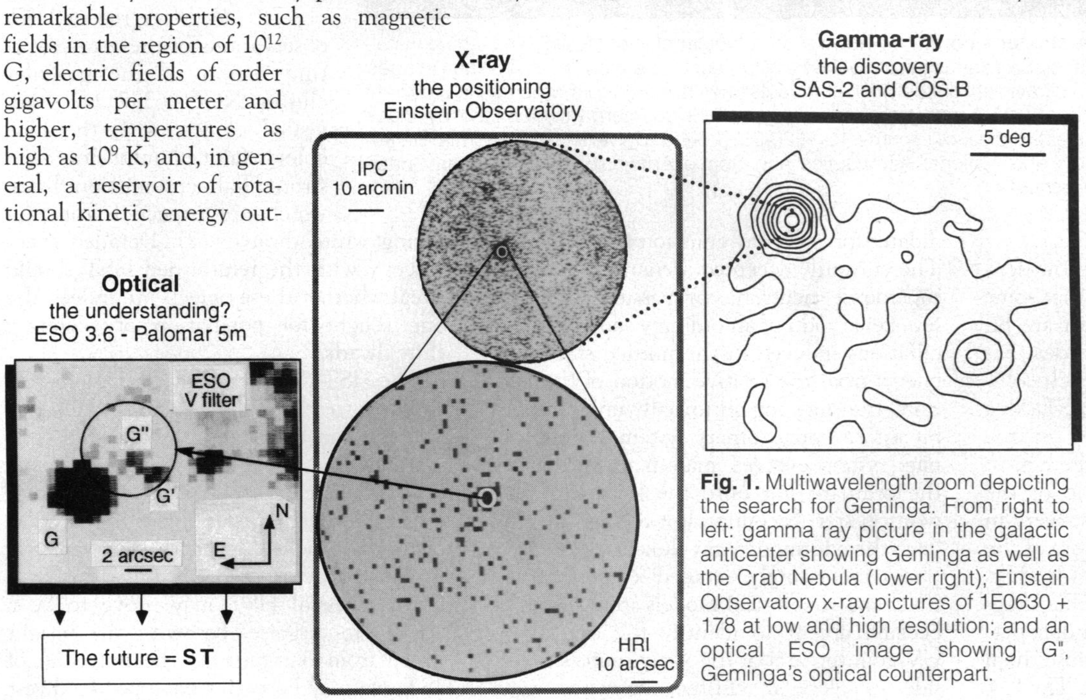

Fig. 1. Multiwavelength zoom depicting the search for Geminga. From right to left: gamma ray picture in the galactic anticenter showing Geminga as well as the Crab Nebula (lower right); Einstein Observatory x-ray pictures of 1E0630+178 at low and high resolution; and an optical ESO image showing G", Geminga's optical counterpart.

For a better understanding of Geminga, the only remaining hope was in deep optical observations. A first deep exposure was obtained from the Canada-France-Hawaii 3.6-m telescope on Mauna Kea, in 1984. Three candidate objects were seen in the 1E0630+178 error circle, dubbed (with little imagination) G, G', and G", in order of increasing magnitude. The first of these, of 20th magnitude, was the brightest and the only one whose spectrum could subsequently be taken: It turned out to be a normal field star, a chance coincidence. Working on the other two was much more difficult and required, over several years, the

The author is at the Istituto di Fisica Cosmica, Consiglio Nazionale delle Ricerche, 20133 Milan, and at the Universita di Cassino, 03043 Cassino, Italy.

use of the biggest telescopes in the world by several groups in the United States and Europe. The break came in 1987–1988, when the colors of G" were recognized to be markedly bluer than all surrounding field stars. This was quite a result in itself because G", with a magnitude between 25 and 26, has a photon flux comparable to that of a candle on the surface of the moon seen at the Earth. If G" was the optical counterpart of 1E0630+178, then the optical to x-ray flux ratio was similar to Vela's, strengthening the case that the source was a neutron star.

Final confirmation of this link came, unexpectedly, in 1992, starting with observations by the Roentgen Satellite (ROSAT), the German, United States, and United Kingdom x-ray satellite, which found the x-ray flux from 1E0630+178 to be pulsed, with a periodicity of about 0.25 s. This clinched the case for a neutron star and provided a tool for further identification. At that time, NASA had recently launched the Compton Gamma Ray Observatory (CGRO), and its high-energy detector, the Energetic Gamma Ray Experiment Telescope (EGRET), keeping Geminga under constant scrutiny, quickly saw the same pulsation in gamma ray photons. The case for the identification of the x-ray–emitting neutron star 1E0630+178 with Geminga was closed.

The accuracy of the data made it possible to measure the change of pulsation period with time, a result of the slowing of the neutron star's rotation, and it was then possible to predict the period of Geminga during the 1975–1982 COS-B measurements, and even during the 1972–1973 SAS-2 studies. When those data were revisited, the pulsation was readily apparent, although with much worse statistics; it can be firmly stated that the pulsation could not have been deduced from the early observations because of the paucity of the gamma ray photons.

The ratio of the observed gamma ray flux to the global energy output of a neutron star with Geminga's rotation characteristics (its period and period derivative) showed that the object could not be at a distance much in excess of 1000 light years—it must be very local, in other words. Because neutron stars generally have high space velocities (hundreds of kilometers per second), it seemed likely that the proper motion of G" could be detected, if indeed this was the optical counterpart of Geminga. Comparison of 1984 and 1987 images with one image from the European Southern Observatory's (ESO's) New Technology Telescope (NTT) on 4 November 1992 revealed a very rapid motion of 170 marc sec year^{-1} across the sky. This finding confirmed that G" is a nearby, intrinsically underluminous object (compared to a normal star) and confirms it as the optical identification of Geminga, whose neutron star nature had been established through the x-ray and gamma ray pulsations.

The Geminga story is a nice example of the power of multiwavelength astronomy for neutron star work. It is the only identification of a neutron star through its gamma ray emission, making it a unique example among the more than 550 radio pulsars now known. In the last couple of years, however, the synergism of the contemporaneous ROSAT and CGRO missions, with help from the most powerful ground-based optical telescopes, has added to the database of isolated neutron stars. So far, ROSAT has now found nearly 20 such sources in soft x-rays, in most cases their emission being explicable as thermal radiation from hot neutron star surfaces. In gamma rays, the CGRO has observed, as well as the Crab, Vela, and Geminga pulsars, pulsed emission from PSR 1706-44, PSR 1055-52, and PSR 1509-58. For all of them, the high-energy emission is a significant fraction of the total; for PSR 1055-52, it may be the dominant energy output.

In the optical domain, observations of the Crab, Vela, and Geminga have been complemented with the secure identification of PSR 0540-69, the first isolated neutron star seen in the Large Magellanic Cloud. More recently, tentative identifications have been proposed for PSR 0656 + 14 (one of the ROSAT objects) and for PSR 1509-58, a high-energy emitter. The latter is of special interest: It has the highest period derivative (slowing down of its rotation) and the highest magnetic field among all neutron stars. A recent deep observation, again with ESO's NTT, found an excellent candidate for the optical counterpart, of 22nd magnitude. If confirmed by timing measurements, this result would require a serious reassessment of pulsar emission theory. Even more interesting are the conclusions reached by comparing the preferred energy output with the age of the objects. Two monotonic trends are apparent: As neutron stars get older, they increase their gamma ray output and decrease the fraction of their luminosity emerging in visible light.

Taking Stock of Gamma Ray Bursts

Dieter H. Hartmann

Astrophysical gamma ray bursts (GRBs), discovered by chance some 20 years ago, are baffling; they are brief, energetic, unpredictable, variable, and do not repeat. For the past 3 years, the Burst and Transient Source Experiment (BATSE) on board the orbiting Compton Gamma Ray Observatory (CGRO) has detected on average one cosmic GRB per day, an event rate almost matched by the publication rate in the field. To help readers take advantage of this active corner of the scientific stock market, I shall discuss the reasons for the GRB boom and some possible pitfalls.

Burst durations range from hundredths of a second to a thousand seconds, with recent convincing evidence for a bimodal duration distribution (*1–3*). Photon energies are typically 1 MeV, with significant emission above 100 MeV but little in the x-ray band. Bursts occur randomly in time and position on the sky; they are distributed isotropically in direction and do not repeat [three sources are known to have had repeated outbursts, but spectrally and in mean photon energy, these three do not resemble classical GRBs and are thought to constitute the distinct class of Soft Gamma Repeaters (SGRs)].

Light curves of GRBs show significant count rate variations on time scales as short as milliseconds; this represents a light travel distance of only 300 km, indicating that the emission is from rather compact astrophysical sites. Burst spectra are in general featureless, but in some cases, low-energy (10- to 100-keV) absorption features have been seen. If interpreted in terms of magnetic resonances in the photon-electron interaction, field strengths of some teragauss are implied, similar to what is inferred in radio pulsars, which are rapidly rotating neutron stars. There is occasional evidence of emission features at about 400 keV, which can be interpreted as the 511-keV electron-positron annihilation line redshifted by the gravitational field of a solar mass neutron star. The existence of these lines has been controversial, but they lent weight to GRB models involving neutron stars.

The spatial distribution of the 10^8 to 10^9 galactic neutron stars, inferred from pulsar studies, resembles the disk of stars but with a larger scale height, say 500 pc. Because the burst distribution shows no sign of the

The author is in the Department of Physics and Astronomy, Clemson University, Clemson, SC 29634.