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Pulsars and isolated neutron stars

HISTORICAL OVERVIEW

The idea of neutron stars can be traced back to the early 1930s, when Subrahmanyan Chandrasekhar, while investigating the physics of stellar evolution, discovered that there is no way for a collapsed stellar core with a mass more than 1.4 times the solar mass, $M_\odot$, to hold itself up against gravity once its nuclear fuel is exhausted (Chandrasekhar 1931). This implies that a star left with $M > 1.4\,M_\odot$ (the Chandrasekhar limit) would keep collapsing and eventually disappear from view. After the discovery of the neutron by James Chadwick in 1932, Lev Landau was the first to speculate on the possible existence of a star composed entirely of neutrons (Landau 1932, Rosenfeld 1974). Using the newly established Fermi–Dirac statistics and basic quantum mechanics, he was able to estimate that such a star, consisting of $\sim 10^{57}$ neutrons, would form a giant nucleus with a radius of the order of $R \sim (\hbar/m_n c)(\hbar c/G m_n^2)^{1/2} \sim 3 \times 10^5$ cm in which $\hbar$, c, G and m_n are the rationalized Planck constant, the speed of light, the gravitational constant, and the mass of the neutron. In view of the peculiar stellar parameters, Landau called these objects *unheimliche Sterne* ("weird stars"), expecting that they would never be observed because of their small size and expected low optical luminosity.

Walter Baade and Fritz Zwicky were the first to propose the idea that neutron stars could be formed in supernovae (Baade and Zwicky 1934). The first models for the structure of neutron stars were worked out in 1939 by Robert Oppenheimer and George Volkoff, who calculated an upper limit for the neutron star mass. Using general relativistic equilibrium equations and assuming that the star is entirely described by an ideal (i.e., non-interacting) Fermi gas of neutrons, they found that any star more massive than $3M_\odot$ (the Oppenheimer–Volkoff limit) will suffer runaway gravitational collapse to form a black hole (Oppenheimer and Volkoff 1939). Unfortunately, their pioneering work did not predict anything astronomers could actually observe, and the idea of neutron stars was not taken seriously by the astronomical community. Neutron stars therefore remained in the realm of imagination for nearly a quarter of a century, until in the 1960s a series of epochal discoveries were made in high-energy and radio astronomy.

X-rays and gamma rays can be observed only from above the Earth's atmosphere (X-rays are absorbed at altitudes of 20–100 km), which requires detectors to operate from high-flying balloons, rockets, or satellites. One of the first X-ray detectors brought to space was launched by Herbert Friedman and his team at the Naval Research Laboratory in order to investigate the influence of solar activity on the propagation of radio signals in the Earth's atmosphere (Chapter 12). Using simple proportional counters put on old V2 (captured in Germany after World War II) and Aerobee rockets, they became the first to detect X-rays from the very hot gas in the solar corona. However, the intensity of this radiation was found to be a factor 10^6 lower than that measured at optical wavelengths. In the late 1950s it was therefore widely believed that all other stars, much more distant than the Sun, should be so faint in X-rays that further observations at that energy range would be hopeless. However, results from high-energy cosmic ray experiments suggested that there exist

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celestial objects (e.g., supernova remnants) that produce high-energy cosmic rays in processes which, in turn, may also produce X-rays and gamma rays (Morrison *et al*. 1954, Morrison 1958). These predictions were confirmed in 1962, when the team led by Bruno Rossi and Riccardo Giacconi accidentally detected X-rays from Sco X-1. With the aim of searching for fluorescent X-ray photons from the Moon*, they launched an Aerobee rocket on 12 June 1962 from White Sands, New Mexico with three Geiger counters as the payload, each having a $\sim 100°$ field of view and an effective collecting area of about $10\,\mathrm{cm}^2$ (Giacconi 1974). The experiment detected X-rays not from the Moon but from a source located in the constellation Scorpius, dubbed Sco X-1, which is now known to be the brightest extrasolar X-ray source in the sky. Evidence for a weaker source in the Cygnus region and the first evidence for the existence of a diffuse isotropic X-ray background were also reported from that experiment (Giacconi *et al*. 1962). Subsequent flights launched to confirm these first results detected Tau X-1, a source in the constellation Taurus that coincided with the Crab Supernova Remnant (Bowyer *et al*. 1964). Among the various processes proposed for the generation of the detected X-rays was thermal radiation from the surface of a hot neutron star (Chiu and Salpeter 1964), and searching for this radiation became a strong motivation for the further development of X-ray astronomy. However, the X-ray emission from the Crab Supernova Remnant was found to be of a finite angular size (~ 1 arcmin), whereas a neutron star was expected to appear as a point source. Thus, the early X-ray observations were not sensitive enough to prove the existence of neutron stars. This was done a few years later by radio astronomers.

In 1967, Jocelyn Bell, a graduate student under the supervision of Antony Hewish at Cambridge University, England, came across a series of pulsating radio signals while using a radio telescope specially constructed to look for rapid variations in the radio emission of quasars. These radio pulses, 1.32 seconds apart and with remarkable clock-like regularity, were emitted from an unknown source in the sky at RA $19^{\mathrm{h}}\ 20^{\mathrm{m}}$, and dec. $+23°$. Further observations refined the pulsating period to 1.33730113 seconds. The extreme precision of the period suggested at first that these signals might be generated by extraterrestrial intelligence. They were subsequently dubbed LGM1, an abbreviation of "Little Green Man 1" (Bell 1977). However, when other similar sources were detected, it became clear that a new kind of celestial object had been discovered. The link between these pulsating radio sources, which were called pulsars, and rapidly spinning neutron stars was provided by Franco Pacini (1967, 1968) and Thomas Gold (1968, 1969). Pacini, then a young postdoctoral worker at Cornell University, had published a paper a few months before the discovery by Bell and Hewish in which he proposed that the rapid rotation of a highly magnetized neutron star could be the source of energy in the Crab Nebula. This prediction was based on the pioneering work of Hoyle *et al*. (1964), who had proposed that a magnetic field of $10^{10}\,\mathrm{G}$ might exist on a neutron star at the center of the Crab Nebula. The most fundamental ideas on the nature of the pulsating radio sources were published by Gold (1968, 1969) in two seminal *Nature* papers. In these papers Gold introduced the concept of the rotation-powered pulsar which radiates at the expense of its rotational energy – the pulsar spins down as rotational energy is radiated away – and recognized that the rotational energy is lost via electromagnetic radiation from the rotating magnetic dipole and emission of relativistic particles. The particles are accelerated in the pulsar's magnetosphere along the curved magnetic field lines and emit the observed intense curvature and synchrotron radiation. (When a charged relativistic particle moves along a curved magnetic field line, it is accelerated tranversely and radiates. This curvature radiation is closely related to the synchrotron radiation caused by gyration of particles around the magnetic field lines.)

Since those early days of pulsar astronomy more than a thousand radio pulsars have been discovered (see, e.g., the catalog by Taylor *et al*. (1993), which lists about half of them). The discovery of the first radio pulsar was very soon followed by the discovery of the two most famous pulsars, the fast 33 ms pulsar in the Crab Nebula (Staelin and Reifenstein 1968) and the 89 ms pulsar in the Vela supernova remnant (Large *et al*. 1968). The fact that these pulsars are located within supernova remnants provided striking confirmation that neutron stars are born in core collapse supernovae from massive main sequence stars. These exciting radio discoveries triggered subsequent pulsar searches at nearly all wavelengths.

Cocke *et al*. (1969) discovered optical pulses from the Crab Pulsar, whereas its X-ray pulsations in the 1.5–10 keV range were discovered by Friedman's group at the Naval Research Laboratory (Fritz *et al*. 1969) and by the team at the Massachusetts Institute of Technology (Bradt *et al*. 1969) three months later. Using a plastic scintillator platform, Hillier *et al*. (1970) flew a balloon-borne experiment over southern England and detected its pulsed gamma rays at a $\sim 3.5\sigma$ level at energies greater than 0.6 MeV. These early multi-wavelength observations showed that the pulses are all phase aligned, with a pulse profile which was very nearly the same at all wavelengths, suggesting a common emission site for the radiation. Moreover, the power observed at the high photon energies exceeded that in the optical band by more

* The Moon was selected as a target because it was expected that a state-of-the-art detector available at that time would not be sensitive enough to detect X-rays from extrasolar sources. "We felt … that it would be very desirable to consider some intermediate target which could yield concrete results while providing a focus for the development of more advanced instrumentation which ultimately would allow us to detect cosmic X-ray sources" (Giacconi 1974).

than two orders of magnitude, justifying the need for more sensitive satellite-based X-ray and gamma-ray observatories to perform more detailed investigations of the emission mechanism of pulsars and to survey the sky for other X-ray and gamma-ray sources.

The first Earth-orbiting mission dedicated entirely to celestial X-ray astronomy, SAS 1 (Small Astronomy Satellite 1), was launched by NASA in December 1970 from a launch site in Kenya. The observatory, later named Uhuru (which means "freedom" in Swahili), was sensitive in the range 2–20 keV and equipped with two sets of proportional counters having a collecting area of 840 cm^2 (Giacconi *et al.* 1971). It was designed to operate in survey mode, allowing for the first time a scan of the whole sky with a sensitivity of 1.5×10^{-11} erg s^{-1} cm^{-2}. In over two years of very successful operation, 339 new X-ray sources were detected (Forman *et al.* 1978): accreting binaries, supernova remnants, Seyfert galaxies, and clusters of galaxies. By far the largest sample of objects was found to belong to the group of accretion-powered pulsars – neutron stars in binary systems accreting matter from a companion star. As the matter spirals onto the neutron star's surface or heats up in an accretion disk, strong X-radiation is emitted (Chapter 32).

The next major step in high-energy astronomy was the launch in November 1972 of SAS 2, the first satellite dedicated exclusively to gamma-ray astronomy (Fichtel *et al.* 1975). The detector, a spark chamber, was sensitive in the energy range 35–1000 MeV. Although the mission lasted only seven months and was ended by a failure of the low-voltage power supply, its measurements confirmed the existence of the gamma-ray pulses from the Crab (Kniffen *et al.* 1974) and discovered the gamma-ray pulses from the Vela Pulsar (Thompson *et al.* 1975), which was found to be the strongest gamma-ray source in the sky. The Vela light-curve was characterized by two relatively sharp peaks, separated by 0.4 in phase (as observed for the Crab) but not phase aligned with the radio and optical pulses.

In addition, a few unidentified gamma-ray sources were detected, among them Geminga, a faint source in the Gemini region from which ~100 gamma-ray photons had been recorded, but which was not finally identified for another 20 years.* Gamma-ray astronomy, from its beginning, was often hampered by the relatively small number of detected photons and large position error boxes, typically $\sim 0.5° - 1°$. This position uncertainty strongly complicated follow-up observations for optical and X-ray counterparts. Scientific publications describing data analysis techniques optimized for "sparse data," particularly the timing analysis aimed at pulsation searching, were therefore always valued highly.

The first complete and detailed gamma-ray map of the Galaxy was provided by the ESA mission COS-B, launched in August 1975. Developed by a group of European research laboratories known as the Caravane Collaboration (formed of members from MPE-Garching, CEN-Saclay, SRON-Leiden (today Utrecht), IFCAI-Palermo, CNR-Milano, and SSD-ESTEC), the satellite carried two scientific payloads: a digital spark chamber, sensitive in the range 0.03–5 GeV, and a 2–12 keV collimated proportional counter that was used as a pulsar synchronizer. The on-board clock calibration was not very accurate, so the latter instrument was used to ensure the synchronization of the X-ray and gamma-ray pulses from isolated pulsars, like the Crab and Vela Pulsars, and accreting pulsars in X-ray binaries. It was further used to determine pulsar ephemerides from the temporal analysis of X-ray data, independently of the availability of exact radio ephemerides. The high sensitivity of the gamma-ray detector allowed Kanbach *et al.* (1980) to conduct the first detailed temporal and spectral study of the Vela Pulsar in the range 0.05–3 GeV. The pulsar's spectrum was found to be represented by a power law, $dN/dE \propto E^{-\alpha}$ (with a photon index of $\alpha = 1.89 \pm 0.06$ for the phase-averaged spectrum), but appreciable differences of the photon index were detected for different pulsar phases (e.g., the inter-pulse emission, first detected in the COS-B data, was found to have the hardest spectrum). The COS-B observations of the Crab Pulsar provided much improved photon statistics which resulted in a more accurate pulse profile (Wills *et al.* 1982) and detailed spectral studies (Clear *et al.* 1987).

Many radio pulsars had been observed by the mid-1970s, and two of them, the Crab and Vela Pulsars, had been detected at high photon energies. Although the interpretation of both isolated and accreting pulsars as neutron stars with enormous magnetic fields, $\sim 10^{12}$ G, had been generally accepted, there was no direct evidence for the existence of such huge fields. The evidence came from a remarkable spectral observation of Her X-1, an accreting binary pulsar discovered with Uhuru by Tananbaum *et al.* (1972). On 3 May 1976, a team of the Max-Planck Institut für extraterrestrische Physik in Garching and the Astronomische Institut of the University of Tübingen, led by Joachim Trümper, launched from Palestine, Texas a balloon equipped with a collimated NaI scintillation counter and a NaI–CsI–phoswich detector, sensitive in the range 15–160 keV. They easily detected the 1.24 s pulsations up to 80 keV (Kendziorra *et al.* 1977). However, when Bruno Sacco and Wolfgang Pietsch attempted to fit the observed spectrum with usual continuum spectral models, they found that a one-component continuum model could not represent the data – all fits gave unacceptably large residuals at ~40–60 keV. Further data analysis

* The source was dubbed Geminga, a pun in Milanese dialect in which *gh'é minga* means "it is not there" or "it does not exist," by Giovanni Bignami – See Bignami and Caraveo (1996) for a comprehensive description of the Geminga story, from the first discovery to the final identification. It is amusing to note that the name inspired Eric Cohez to choose the title of his science fiction book *Geminga: la civilisation perdue*.

confirmed that the spectral feature was not an artifact (e.g., due to incomplete shielding of the in-flight calibration source, ^{241}Am, which emitted a spectral line at $E = 59.5\,\mathrm{keV}$). It was Joachim Trümper who first recognized that the excess emission at 58 keV (or an absorption feature at 42 keV, depending on interpretation; Figure 1) could be associated with the resonant electron cyclotron emission or absorption in the hot polar plasma of the rotating neutron star. The corresponding magnetic field strength would then be 6×10^{12} or 4×10^{12} G (Trümper *et al.* 1978). This observation provided the first direct measurement of a neutron star's magnetic field and confirmed the basic theoretical predictions that neutron stars are highly magnetized, rapidly spinning, compact objects.

Beginning in 1977, NASA launched a series of large scientific payloads called High Energy Astrophysical Observatories (the dramatic history of the HEAO project and the experiments aboard HEAO satellites are described in lively fashion by Wallace Tucker (1984)): HEAO 1 (August 1977–January 1979), HEAO 2 (November 1978–April 1981), and HEAO 3 (September 1979–May 1981). Particularly important results on isolated neutron stars, among many other X-ray sources, were obtained with HEAO 2, widely known as the Einstein X-ray observatory (Giacconi *et al.* 1979), which carried the first imaging X-ray telescope on a satellite. Among four focal plane detectors of Einstein, two proved to be particularly useful for detecting and studying isolated neutron stars. The High Resolution Imager (HRI), a micro-channel plate detector, sensitive in the 0.15–4 keV energy band, with about 5 arc seconds angular resolution, was designed to use the imaging capability of the X-ray telescope. However, it had no energy resolution and its field of view was small, ~25 arcmin. The Imaging Proportional Counter (IPC), the workhorse of the observatory, could detect weaker sources than the HRI and had a wider field of view, ~1°, but its imaging resolution was about 1 arcmin. It was capable of studying spectra with modest energy resolution in the range 0.2–4 keV.

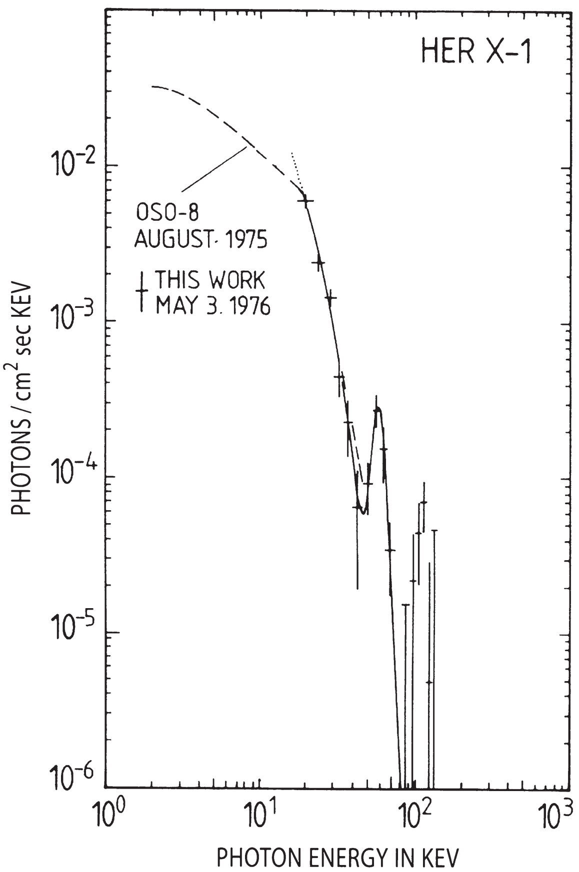

Figure 1 Unfolded X-ray spectrum from Her X-1, showing the first measurement of a cyclotron line in a pulsed spectrum of an accreting neutron star. (From Trümper *et al.* 1978.)

Einstein investigated the soft X-radiation from the previously known Crab and Vela Pulsars and resolved the compact nebula around the Crab Pulsar (Harnden and Seward 1984). It discovered pulsed X-ray emission from two other very young pulsars, PSR B0540–69 in the Large Magellanic Cloud (Seward *et al.* 1984) and PSR B1509–58 (Seward and Harnden 1982), with periods of 50 ms and 150 ms respectively. Interestingly, these pulsars were the first ones discovered in the X-ray band and only subsequently detected at radio frequencies. No pulsations from the Vela Pulsar were found in the soft X-ray band.

Einstein also detected three middle-aged radio pulsars, PSR B0656+14 (Córdova *et al.* 1989), B1055 − 52 (Cheng and Helfand 1983), and B1951+32 (Wang and Seward 1984). Also, X-ray counterparts of two nearby old radio pulsars, PSR B0950+08 and B1929+10, were identified, based on positional coincidence (Seward and Wang 1988). In addition, many supernova remnants were mapped – 47 in our Galaxy (Seward 1990) and 10 in the Magellanic Clouds (Long and Helfand 1979) – and several neutron star candidates were detected as faint, soft point sources close to the centers of the supernova remnants such as RCW 103 (Tuohy and Garmire 1980), PKS 1209 − 51/52 (Helfand and Becker 1984), Puppis A (Petre *et al.* 1982), and Kes 73 (Kriss *et al.* 1985).

Some additional information on isolated neutron stars was obtained by Exosat (European X-ray Observatory Satellite; Taylor *et al.* 1981), which was equipped with a low-energy detector with imaging capability and grating (0.04–2 keV) and a medium-energy proportional counter (1.5–50 keV). In particular, it measured the soft X-ray spectra of the middle-aged pulsar PSR B1055 − 52 (Brinkmann and Ögelman 1987) and of a few neutron star candidates in supernova remnants (e.g., PKS 1209 − 51/52; Kellett *et al.* 1987).

In spite of the major advance in the field of high-energy astronomy provided by the space observatories (particularly by Einstein) in the 1970s and 1980s, the results obtained

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