disk formed from a secular kinematic diffusion of thin disk stars (which would produce a continuity between thin and thick disks). It remains a scenario well in agreement with the present data: the thick disk could have been formed from the dynamical heating of the thin disk during the sink of a small galaxy into the Milky Way. This merging event has to happen at the beginning of the thin disk life time so that the gas can cool again and form stars in the long-lasting thin galactic disk that we see now. This violent bottom-up scenario leaves two important observational signatures. First the thick disk is a separate population distinct from the thin disk and the halo. Second, no gradient can be generated in the thick disk by the event, although a preexisting gradient may survive the merger.

Conclusions

The thick disk population is found from all points of view (density laws, kinematics and metallicities) as a population well separated from the thin disk. It shows no gradient either on abundance[3] or on kinematics. The results emerging from the present study of the correlations between photometry and kinematics give a mounting evidence that the thick disk of the Galaxy is most likely a sequel of a dwarf satellite galaxy merging in the Milky Way disk during the early epoch of this disk. This interpretation emerged from an accurate characterization of the thick disk properties: the scale height and the scale length of this component have been established; its rotation and velocity dispersion turned out to be quite distinct from both the disk itself and the halo. The local density of the thick disk component is twice what was previously assumed and the stellar colours do not reflect any significant chemical gradient.

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REVIEW ARTICLE

A unique and remarkable binary pulsar

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PSR B1259–63 is one of the most remarkable pulsars ever discovered. It is the only pulsar known to be orbiting a main-sequence Be star and forms the 'missing link' in the evolutionary scenario of binary stars. Its orbit is highly elliptical and every 3.5 yr it approaches to within 0.5 AU of its companion star. Its pulse profile is unique among pulsars and shows that the opening angle of its emission cone exceeds 180°. Observations made around the time of closest approach of the two stars show changes in the pulsar's dispersion measure, rotation measure and fractional linear polarization on very short timescales. The pulsar is observed to spin down during the periastron passage. The companion star to the pulsar has been monitored at optical and UV wavelengths. The system is a radio and X-ray transient and has been detected at γ-ray energies, with the high-energy emission probably occurring in a shock front formed by the collision of the two stellar winds.

IN this review paper, I will discuss the remarkable binary pulsar PSR B1259-63. I will start with a general introduction into pulsars and binary systems before moving on to the specifics of the system containing PSR B1259-63. There are an increasing number of excellent conference proceedings and review articles on pulsars in general with varying degrees of complexity. Interested readers should consult refs. 1–11 and the references therein.

Almost 30 years after the discovery of the first pulsar by Hewish *et al.*[12], radio pulsars remain one of the astronomy's most exciting fields. The existence of neutron stars was predicted as early as the 1930s by Baade and Zwicky[13], who speculated that when a high-mass star (typically 5 or more solar masses, $M_{\odot}$) ends its life in the spectacular event known as a supernova explosion, it should leave behind a dense stellar core. Although a blue star at the centre of the Crab Nebula was postulated to be such a neutron star[14], it was little thought that they would be detectable. In 1967, however, these neutron stars were serendipitously discovered by a group of radioastronomers working at Cambridge University in the UK. The name pulsars (a contraction of the two words *pulsating stars*) is a misnomer; the stars rotate rather than pulse and the principal characteristic of a pulsar is its incredibly stable rotation rate. The radioemission originates from near the magnetic pole and the misalignment between the rotation and magnetic axes produces a regular pulse of radiation for an observer on Earth (like the oft-quoted analogy with a lighthouse).

Pulsars are now known to be highly magnetized, rapidly rotating neutron stars which originate from the supernova explosions of high-mass stars. Pulsars have masses in a tight range around 1.4 $M_{\odot}$ and have diameters of only ~20 km; this implies a stellar density in the region of 10^{17} kg m^{-3}. Almost 600 have now been discovered and catalogued[15]; all bar a few are located within our own Galaxy. Their spin periods range between 0.00155 and 5.4 s and their inferred magnetic fields lie between 10^4 and 10^9 T. The youngest known pulsar is 900 years old in the Crab Nebula. The oldest pulsars have ages in excess of 10^9 years, comparable to the age of the Galaxy. All pulsars are observed to spin down with time due to rotational energy losses from relativistic particles streaming from the high magnetic field.

Only ~2% of pulsars are part of a binary system. However, their importance is not proportional to their number and they provide many valuable insights into the physics and the formation and evolution of neutron star systems and their progenitors. Before the discovery of PSR B1259–63, all the companions to known binary pulsars were degenerate stars, either white dwarfs or other neutron stars. The evolutionary route of double neutron star systems is thought to occur as follows[7]: Two high-mass stars are in a mutual orbit; the more massive of the two stars evolves first and then explodes in a supernova explosion. In rare cases, the system remains bound and consists of a high-mass star and a young neutron star[16]. The high-mass stars eventually evolve, and the system goes through a high-mass X-ray binary phase (HMXB) when material from the evolved star accretes onto the neutron star surface. Eventually, the high-mass star explodes in its turn and, if the system remains bound, a double neutron star system remains. All the steps of this evolutionary chain had been observed (most famously perhaps for the double neutron star system PSR B1933+16, for which the discoverers[17] won the 1993 Nobel Prize for Physics) except the second step – the neutron star, high-mass star pair before it evolves into an HMXB. This 'missing link' was found with the discovery of PSR B1259–63 (ref. 18) and an important piece in the evolutionary jigsaw fell into place. A further example of such a system has subsequently been discovered[19,20].

It turned out that PSR B1259–63 was orbiting a $10 M_{\odot}$ star known as a Be star (described in more detail below). Be stars[21] themselves are rather strange objects. Most stars show spectral lines only in absorption; however, the Be stars are characterized by having the Balmer series of hydrogen in emission. In the early 1930s, this was interpreted to mean that the star had a disk of material surrounding its equator which had been thrown off due to centrifugal forces from the rapidly rotating underlying star[22]. This simple model is still prevalent today, although observations, particularly at UV wavelengths, have found that this cannot be the whole story. There remains no convincing theoretical model of Be stars. The general picture, however, is that Be stars have a hot, tenuous, fast-moving wind which is thought to originate from the stellar poles. They also have a disk of material which is cool, dense and slow-moving and which follows Keplerian orbits at least for a few tens of stellar radii. In the simplest model the disk can be characterized by two parameters: an opening angle and a radial power law distribution of electron densities within this envelope[23].

Discovery

PSR B1259–63 was discovered during a search for young, distant pulsars in the galactic plane using the Parkes 64 m telescope located in NSW, Australia[24]. For a variety of reasons, the search was conducted using an observing frequency centred at 1520 MHz rather than the 400 MHz commonly employed in pulsar searches. This high-frequency turned out to be rather valuable as, most unusually for pulsars, PSR B1259–63 cannot be detected at low frequencies in short integration times.

The pulsar was interesting to us right from the moment of discovery. It had the shortest spin period (47 ms) of any of the pulsars discovered in the survey and had a rather curious double-pulse profile reminiscent of the archetypal young pulsar in the Crab Nebula (PSR B0531+21). After a successful attempt to measure the period change over a few days, we concluded that the pulsar was probably young. This encouraged us to look for a supernova remnant around the pulsar, but to our disappointment an image of the region with the Molonglo Synthesis Telescope (MOST) revealed nothing of interest in the pulsar's vicinity.

By the middle of 1990 we realized that the pulsar was not behaving exactly as it should. In two consecutive timing observations the pulsar was extremely weak before reappearing about a month later at its usual strength. As the timing programme continued and more data points were obtained, it was evident that the pulsar's behaviour could not be explained with a simple period and period-derivative, and in early 1991 we came to the conclusion that the pulsar was a member of a long-period binary system. The most remarkable thing about the binary companion is that it had to have a mass greater than 2 $M_\odot$ and this implied that the companion was either a black hole or a high-mass star. Both possibilities were extremely interesting – all other binary pulsars to that date, of which there are anyway very few, had either white dwarf companions (with mass less than 1 $M_\odot$) or neutron star companions (with masses between 1.2 and 1.6 $M_\odot$).

A sub-arcsecond position using the Australia Telescope Compact Array (ATCA) was obtained and it turned out that a well-known 10th magnitude Be star, SS 2883, was located within the ATCA error box. Thus, the companion was a main-sequence star with a mass of ~10 $M_\odot$, the first such system discovered and an important system for our understanding of the evolutionary sequence of the millisecond pulsars. When the paper announcing the discovery of the system was published[18], not enough data had been obtained to allow an accurate determination of the orbital parameters; indeed, it turned out that the errors quoted in the parameters were much too optimistic. However, the general shape of the orbit was correct; it was highly eccentric ($e \sim 0.9$) and the binary period was in excess of a few years. This remains the orbit with the highest eccentricity out of all the known neutron star binary systems. This high eccentricity implies that the pulsar comes very close to its companion star at closest approach ('periastron').

Waiting for periastron

Although by 1992 it was apparent that periastron was still a year or more away, there were plenty of experiments needing to be done. The programme to monitor the pulsar in the radio was continuing, with data being obtained roughly every two weeks. As the time baseline increased, the binary parameters became better determined, and by early 1993 we were confident of the numbers and published them in an IAU telegram[25] with the prediction that the next periastron would occur on 9 January 1994.

At optical wavelengths, a crude spectrum of the star had been obtained[18], but in April 1993 we used the 3.8 m optical Anglo-Australia Telescope (AAT) to obtain high-resolution spectrum of the prominent hydrogen Balmer lines typical of Be stars as a class. The spectrum showed the higher-order Balmer lines and the He I line in emission and thus confirmed that the star was around spectral type B1 and had a mass of ~10 $M_\odot$ and a radius of ~6 $R_\odot$. This, in turn, implies that the inclination angle of the binary orbit in the plane of the sky is roughly 35°. The optically derived distance of only 1.5 kpc is in contrast to the distance derived from the dispersion measure of 4.5 kpc (ref. 26); it is likely that the optical value is closer to the truth. The equatorial stellar rotation velocity is ~180 km s^{-1}; given the star's spectral type, the velocity is expected to be somewhat higher than this. If we ascribe the velocity difference to an inclination angle effect then the equator of the star is also inclined at 35° to the line of sight, similar to the binary orbit. Although

Table 1. Observed and derived parameters for PSR B1259–63 (from ref 27)

Right ascension, α (J2000)	$13^h\ 02^m\ 47^s$ 68(2)
Declination, δ (J2000)	−63° 50′ 08″ 6(1)
Period, P	47 762053919(4) ms
Period derivative, $\dot{P}$	2 2793(4) × 10^{-15}
Epoch of period	MJD 48053 44
Dispersion measure, DM	146 75(8) cm^{-3} pc
Orbital period, P_b	1236 79(1) days
Projected semimajor axis, $a \sin i$	1295.98(1) light s
Longitude of periastron, w	138 6548(2)°
Eccentricity, e	0 869836(2)
Epoch of periastron	MJD 48124 3581(2)
Magnetic field, B	3 3 × 10^{11} G
Characteristc age, τ_c	0 33 Myr
Mass function, $f(M_p)$	1.53 $M_\odot$
Predicted periastron passage	MJD 49361 2 ≡ 1994 Jan 9 2.

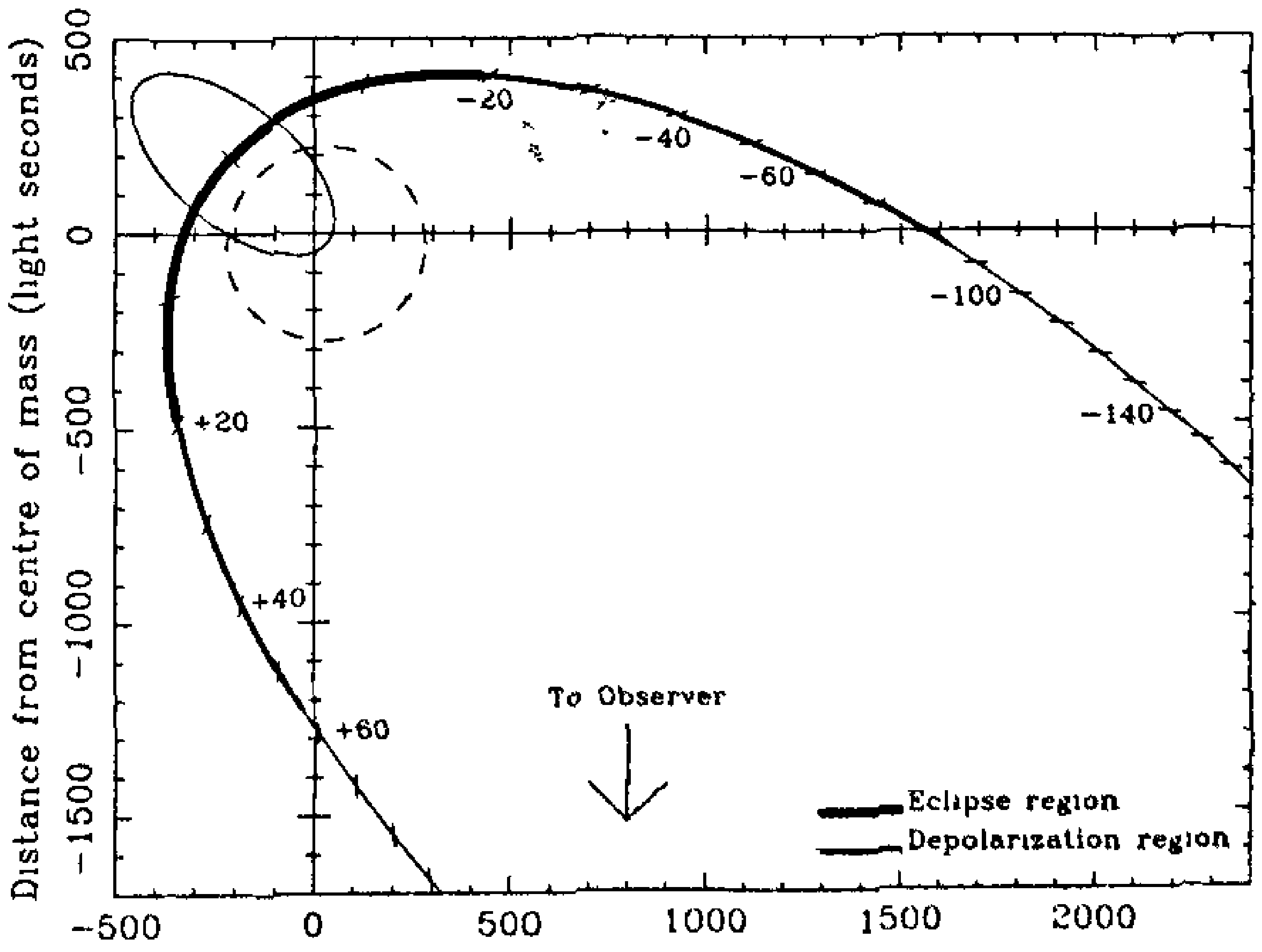

Figure 1. Schematic diagram showing the orbital path of the pulsar and its Be star companion around the time of periastron Tick marks on the pulsar orbit are at 10-day intervals. The orbit of the Be star, assuming a mass of 10 $M_\odot$ for this star, is shown in the top-left corner, and the likely size and position of the optical circumstellar disc at periastron is shown by the dashed circle. The medium-thickness line indicates the portion of the orbit over which the pulsed emission was depolarized, and the full-thickness line indicates the interval over which the pulsar was eclipsed (After ref 40)

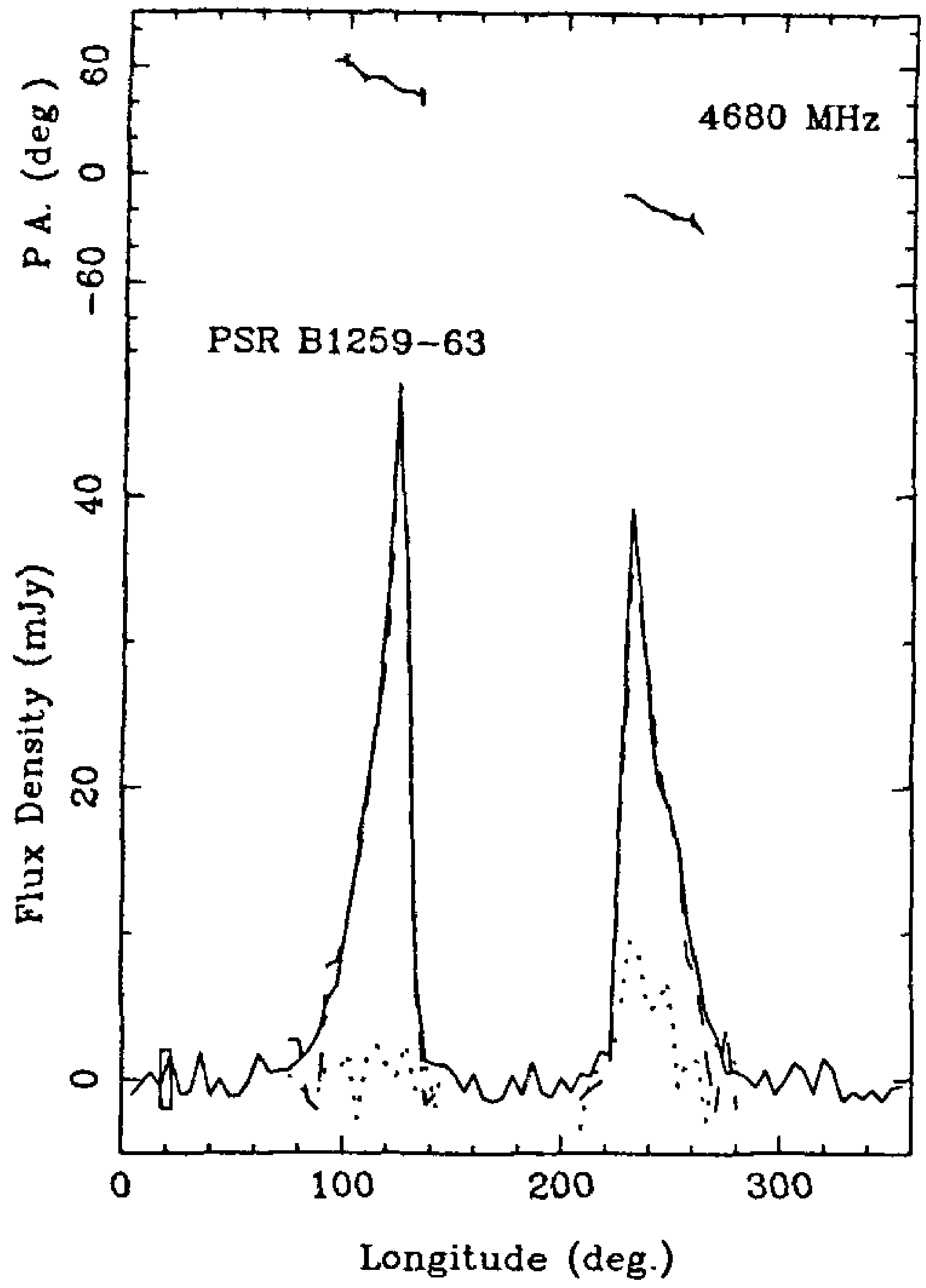

Figure 2 Mean pulse profiles and polarization parameters for PSR B1259–63 at 4.7 GHz. In the lower part, the solid line is the total intensity (Stokes parameter I) profile, the dashed line is the linearly polarized intensity (L), and the dotted line is the circularly polarized intensity (V). In the upper part, the position angle of the linearly polarized part (ψ) is plotted where L is significantly above noise, with $\pm 2\sigma$ error bars on every second point. An error box of amplitude 2σ and width equal to the effective profile resolution (including dispersion smearing across frequency channels) is visible at the left-hand end of the profile baseline. (After ref. 28)

this result is highly model-dependent it does give some indication that the stellar disk and the binary orbit are close to aligned. A combination of the optical results and the improved timing parameters for the pulsar using all the data available up to mid-1993 was published by Johnston *et al.*[27]. The observed spin and Keplerian parameters and a few of the derived parameters of the system are shown in Table 1. A schematic of the pulsar's orbit near the time of periastron is shown in Figure 1.

Radio polarization data for the pulsar were obtained at frequencies ranging between 1500 and 8400 MHz. The data show that both pulses are strongly (80%) linearly polarized at all frequencies[28]. The polarization properties of the pulsar at 4700 MHz are shown in Figure 2, which shows the pulsar in its 'conventional' profile, and this leads one to believe that the pulse shown on the left arrives at the observer before the pulse shown on the right. Remarkably, the polarization data show that convention in this case is flaunted. The data show that the pulsar emission cone must have a very large opening angle (greater than 180°) and that the pulse shown on the right actually arrives first[28]. The data also confirm that the binary inclination angle must lie close to 35°.

Observations had also begun at higher energies. Following an apparent nondetection of the pulsar just prior to apastron at X-ray wavelengths[29], the ROSAT telescope was used to observe the pulsar at two epochs just after apastron[30]. The pulsar was detected on both occasions, the second detection being roughly double the flux of the first. There was no evidence for any pulsed flux at either epoch. Cominsky *et al.*[30] considered various origins of the X-rays and ruled out that they originated from the Be star's hot coronal wind or from Roche-lobe overflow accretion. They concluded that some accretion from the Be star wind must be occurring even at such a large distance from the star. Later, the apparent nondetection was reanalysed[31] and it was found that the pulsar was, in fact, detected at a low flux level; however, this did not alter the basic conclusions in ref. 30.

Meanwhile, the theorists had not been idle. Kochanek[32] was the first out of the starting blocks and he modelled the impact of the pulsar on the equatorial disk of the Be star and the observational consequences for the optical emission lines. King and Cominsky[33] had taken the X-ray observations and proposed that the X-rays originated from low-level accretion from the tenuous (at apastron) Be star wind spherically onto the neutron star. In the model, the equatorial wind speed had to be low, only ~10 km s^{-1} and relatively cool. Later X-ray observations (see below) probably rule out this explanation. Lipunov *et al.*[34] proposed an evolutionary scenario for the pulsar and also predicted that changes in the pulsar's dispersion and rotation measures would be observed at periastron. Finally, shock theory was used [35] to model the interaction between the pulsar wind and the Be star wind and implications of the theory for high-energy observations near periastron were discussed. The conclusions were that the observations should yield a determination of the physical characteristics of both winds.

Periastron

Observations at the time of periastron were carried out from the radio through to γ-ray energies, encompassing UV, optical and X-ray energies.

Careful timing analysis of the pulsar for over 1500 days and two periastron passages came to fruition with the discovery that the pulsar had spun down slightly as a result of its periastron passage[36]. The magnitude of the spin-down is rather small, with a $\Delta P/P$ of $\sim 2 \times 10^{-9}$ and it is argued that this is a result of the so-called 'propeller effect'[37,38]. The slowdown occurs because although the strong magnetic field of the pulsar prevents accretion onto its surface, the incoming material still interacts with the strong magnetic field at the Alfvén radius. The magnetic field 'propels' the material away from the star but at the same time the material imposes a braking torque on the pulsar. Detailed modelling of the effect in this system has been considered by Ghosh[39].

Observations of the pulsar using the Parkes radiotelescope over a few months around periastron have been discussed by Johnston *et al.*[40]. The observations showed changes in the pulsar's dispersion measure, rotation measure, flux density and percentage polarization on short timescales. This is the first time such changes have been observed in any pulsar. Essentially, the pulsar acts as an excellent probe of the wind surrounding the Be star. As the pulsar approaches its companion, it enters denser regions of the Be star's wind and the pulsar's dispersion measure starts to increase. Eventually, due to the clumpy nature of the wind, the pulses themselves become scatter-broadened and this renders the pulsar undetectable at low frequencies. Finally, a combination of pulse scattering and free–free absorption renders the pulsar undetectable for a period of 6 weeks around periastron itself[40]. On egress from the eclipse, the rotation measure and percentage polarization of the pulses varied rapidly over a period as short as a few hours. Melatos *et al.*[41]. looked at detailed modelling of the stellar environment based on the radio observations of the pulsar. They concluded that the pulsar wind cannot dominate the Be star's wind contrary to popular belief and that the best fit to the observed radio data comes from assuming that the Be star has a thick equatorial disk with a exponential density profile. The value of the stellar magnetic field and surface density are consistent with other values found in the literature[42].

Observations of the binary system were made with the ASCA X-ray satellite on three epochs around periastron[43]. The system was detected on all three occasions with an X-ray luminosity of $\sim 10^{34}$ erg s^{-1} just before and just after periastron and about a factor of 2 lower at periastron itself. As with the earlier ROSAT data, no pulsations were detected and accretion onto the neutron star surface as a cause of the X-rays can also be ruled out[43]. The most likely explanation is that magnetohydrodynamic shock acceleration processes between the pulsar and the Be star's wind are the most likely explanation for the X-ray emission. Details of this mechanism will appear in a later publication[44].

Finally, observations at γ-ray wavelengths with GRO[45], in the UV[46], optical[47] and the radio continuum[48] are all still being analysed and the results should appear in the press within this year.

Summary

I have given a brief overview of the discovery of the peculiar binary pulsar PSR B1259–63. It remains one of only two pulsars known to be in orbit around a high-mass main-sequence star. It is the only pulsar to show dynamical changes in its measured parameters and the only radio pulsar to show X-ray and γ-ray transient phenomena.

Most of the observational data are currently in press or in preparation (as of July 1995) and the publication of this material will undoubtedly stimulate further research into this system. The next periastron will occur in mid-1997 and once again both observers and theoreticians will be watching with interest.

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RESEARCH COMMUNICATIONS

A high-precision technique using X-ray reflectivity for the measurement of surface and interface roughness

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Surface and interface roughness plays a crucial role in ultrathin two-dimensional layers. We have set up an X-ray reflectometry facility for the measurement of surface and interface roughness with a precision better than 1 Å. As ion implantation is one of the techniques to fabricate ultrathin buried epitaxial layers, we have explored the effect of MeV ion implantation on surface roughness in two cases: Au-implanted $LiNbO_3(001)$ and Co-implanted Si(111) samples. In both cases we have observed an implantation-induced enhancement of surface roughness. In addition, for the Co-implanted samples, we found unexpected interference fringes with dose-dependent periodicity.

HIGH-quality thin films are necessary for the fabrication of lower-dimensional structures for fundamental studies and for device fabrication in microelectronics. For the growth of high-quality films the role of solid–vacuum and solid–solid interfaces is very crucial. The quality of the thin film and the interfaces should be as good as possible. Therefore, one needs experimental probes to determine this quality. Among the relevant questions to be answered are the following: (i) What is the structure of the ultrathin grown layer, or what is the initial stage of growth? (ii) For a multielemental film, which type of atoms lie in the first atomic layer at the interface? (iii) What is the coordination number of the interface atoms? (iv) What is the distance between adjacent atomic layers across the interface? These questions are answered by using a very powerful technique involving generation of standing waves of X-rays[1–4]. One would also like to know the amount of statistical disorder, or roughness, on the film surface and on the buried film–substrate interface. This information along with the film thickness can be obtained from X-ray specular reflectivity measurements. Both the X-ray standing wave and the X-ray reflectivity measurement techniques are nondestructive and the high penetration power of X-rays enables the probing of buried layers and interfaces.

For the determination of interface roughness, the problem is to determine the correct probability density function for the interface position in the direction of the surface normal. This is mostly a Gaussian distribution. Then the spread in the interface position can be evaluated. X-ray reflectivity under the grazing incidence condition is a well-established technique to investigate this spread in the position of exposed (outer) and buried (inner) interfaces[5].