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A search for the optical counterpart of the binary millisecond pulsar PSR 1855 + 09

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Summary. We report optical observations of the field of PSR 1855 + 09, including accurate astrometry and deep CCD imaging. Contrary to an earlier report we do not detect an optical counterpart of PSR 1855 + 09, and find a lower limit of $m_v = 25.4$ to the apparent visual magnitude of the white dwarf companion star. White dwarf cooling calculations, and the fact that the neutron star was formed before the companion became a white dwarf, imply that the age of the neutron star is in excess of $\sim 1.9 \times 10^9$ yr, reinforcing the idea that old neutron stars must retain a magnetic field $\sim 10^9$ G.

1 Introduction

Optical observations of the binary radio pulsars PSR 0655 + 64 and PSR 0820 + 02 (Kulkarni 1986) show that their companion stars are white dwarfs, as expected from current ideas on the formation and evolution of these systems (Joss & Rappaport 1983; Helfand, Ruderman & Shaham 1983). These observations indicate that the decay of the magnetic fields of neutron stars does not continue below a value of $\sim 10^9$ G (Kulkarni 1986; van den Heuvel, van Paradijs & Taam 1986). We decided to attempt photometry of the 5-ms binary pulsar, PSR 1855 + 09 (Wright & Loh 1986).

2 Observations

PSR 1855 + 09 was observed with the William Herschel Telescope of the Observatorio del Roque de Los Muchachos on La Palma on 1988 June 23, and on 1988 August 4, with a blue coated GEC CCD chip installed at one of the Nasmyth foci. Due to problems associated with this early stage of the commissioning of the telescope, integration times during our first run were limited to a maximum of 300 s. Images were subsequently shifted and added to increase sensitivity. Total integration times were 600 s in white light, 400 s in *V*, 400 s in *B*, and 400 s in *R*. The white light image is shown in Plate 1; the plate scale is 0.1 arcsec per pixel. The seeing was generally 0.8 arcsec or better. The Wright & Loh optical candidate is arrowed.

We found that blind offsetting from a series of nearby SAO stars brought the WHT to a position 4 arcsec from the proposed optical candidate. This technique has an accuracy of slightly greater than 1 arcsec. Subsequent astrometric measurements to determine the pulsar's radio position on the CCD image involved SAO star position measurements on a POSS print using the X–Y measuring machine at the Mullard Space Science Laboratory (accuracy ~ 1.2 arcsec), and AGK_3 star measurements using the coradograph machine at the Royal Greenwich Observatory (accuracy < 1.0 arcsec). All three estimates are consistent with the position circled on Plate 1. The radius of this circle represents an estimate of the error of 1 arcsec. We find no object at this position, and the limiting apparent visual magnitude is ~ 25.4. The nearest star to this position is an $m_v \sim 24$ star ~ 3.5 arcsec to the north–east.

3 Discussion

From its dispersion measure the distance d of PSR 1855 + 09 has been estimated at 350 pc. Since this estimate has an rms uncertainty of a factor of 2 (Lyne, Manchester & Taylor 1983) we will take a range in distance between 175 and 700 pc. For the general direction of PSR 1855 + 09 the visual interstellar extinction A_v is 1.5–2.0 mag kpc^{-1} (Neckel & Klare 1980). From this we find a lower limit to the absolute visual magnitude of PSR 1855 + 09 between $M_v = 14.9$ (for $d = 700$ pc) and $M_v = 19$ (for $d = 175$ pc).

Fast-spinning radio pulsars in wide binary orbits with low-mass white dwarf companions are descendants of low-mass X-Ray binaries in which mass transfer is driven by the secular expansion of the evolving giant companion of the accreting neutron star. From a detailed discussion of the evolution of such systems (Rappaport, Joss & Lewis 1980; Savonije 1987), it appears that there is a unique relation between the final orbital period (after termination of mass transfer) and the mass of the remnant core of the giant star, which is now the white dwarf companion of the radio pulsar. For PSR 1855 + 09, a mass of 0.2 (± 0.03) $M_\odot$ is found from this relation, consistent with the observed mass function of Segelstein *et al.* (1986).

Within the context of this evolutionary model, the neutron star in PSR 1855 + 09 was formed before its white dwarf companion; so an age estimate of the latter, from the time required for it to cool sufficiently to become as faint as we observe it now, can be used to constrain the age of the neutron star.

Detailed cooling models for white dwarfs can be surprisingly well described by the classical theory of Mestel (1952; see also Iben & Tutokov 1984). We have therefore used Mestel's theory (according to which, for a given age, the white dwarf luminosity is proportional to its mass) to scale the cooling curve for a 0.6-$M_\odot$ white dwarf down to 0.2 $M_\odot$ (Shapiro & Teukolsky 1983). We then find for the companion of PSR 1855 + 09 the following relation between the luminosity L (in solar luminosities) and the age t_9 (in units of 10^9 yr)

$$L/L_\odot = 3.33 \times 10^{-4}\, t_9^{-1.4}. \quad (1)$$

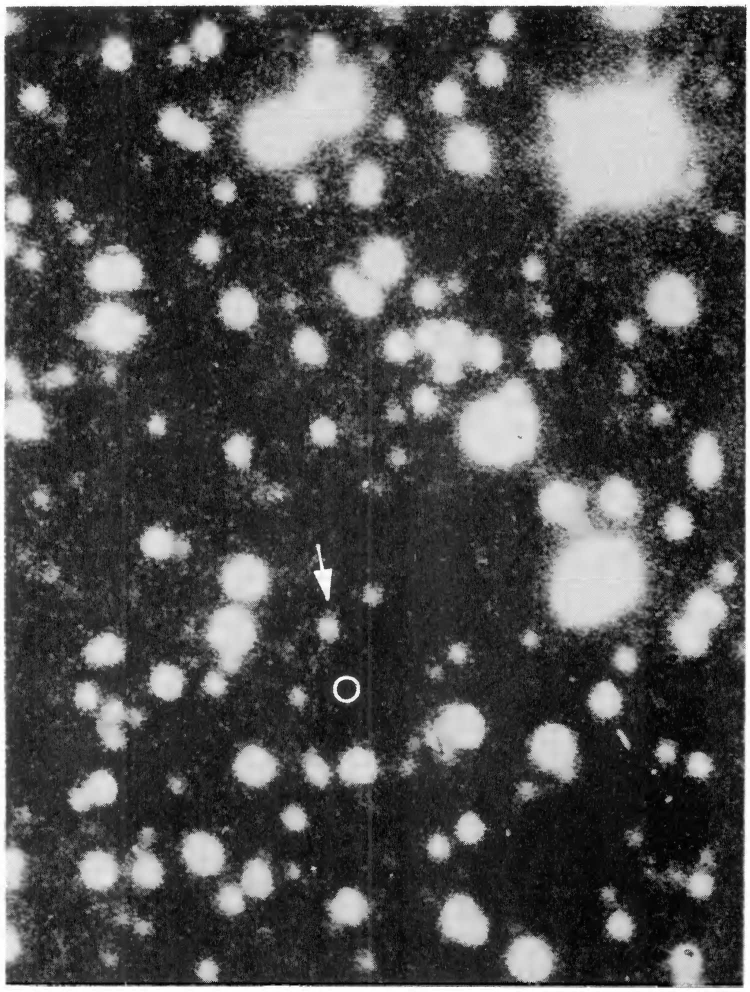

Plate 1. A 600-s white light intergration of the field of PSR 1855 + 09. The image scale is 0.1 arcsec $pixel^{-1}$: dimensions are 40×60 $arcsec^2$. North is left and east is down. The previous optical candidate and our estimate of the radio position are indicated by the arrow and circle, respectively.

To transform the limit on M_v observed above into limits on L, we have used the model atmospheres of Kapranidis (1985) for cool degenerate stars. From these models the monochromatic flux at 5500 Å (i.e. in the *V*-band) emitted at the surface of the white dwarf can be obtained as a function of the effective temperature, T_{eff}. Together with the mass–radius relation for low-mass stars (Zapolski & Salpeter 1969) and a calibration of visual magnitude in terms of observed monochromatic fluxes (Johnson 1966), these models then provide a relation between T_{eff} and M_v (and, of course, L) for a 0.2-$M_\odot$ white dwarf. We note that this relation agrees very well with the results of Winget *et al.* (1987), which are based on a different cooling model (Lamb & Van Horn 1975) as inferred from their fig. 1 and table 1 (for He-rich white dwarfs). From this relation we find that the upper limits on L, corresponding to the lower limits on M_v (14.9 and 19), are 1.3×10^{-4} and $2.2 \times 10^{-5}\ L_\odot$, respectively. The corresponding limits on the age of the white dwarf (and therefore of the neutron star) are 1.9×10^9 and 7×10^9 yr, respectively. We note the comparatively small spread in our age estimate (a factor of ~3.7), despite the much larger uncertainty in the upper limit of the absolute magnitude (~4.1). The limits on the luminosity are not far removed from the value required for crystallization to occur, which strongly affects the subsequent cooling of the white dwarf.

Pulsar wind ablation, a process thought to be occurring in the PSR 1957 + 20 system (Fruchter, Stinebring & Taylor 1988) is unlikely to be occurring in PSR 1855 + 09. Following van den Heuvel & van Paradijs (1988), we estimate $\tau_{evap} \gg$ the Hubble time. This estimate is very sensitive to several parameters, notably the neutron star radius ($\propto R^6$). However, an ablation phase in the past involving a mass loss rate of $\sim 10^{12-13}$ kg s^{-1} could, over 10^9 yr, lead to an increase of the orbital period to its present value.

4 Conclusion

The neutron star in PSR 1855 + 09 must be older than 1.9×10^9 yr, and may be older than $\sim 7 \times 10^9$ yr. Since PSR 1855 + 09 has a magnetic field of $\sim 3 \times 10^8$ G, our result reinforces the idea that, after an initial decay (at a time-scale of $\sim 10^7$ yr), the magnetic fields of neutron stars remain near a level $\sim 10^9$ G.

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