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OPTICAL AND RADIO OBSERVATIONS OF THE BINARY PULSAR 1855+09: EVOLUTION OF PULSAR MAGNETIC FIELDS AND LOW-MASS WHITE DWARF COOLING

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ABSTRACT

Secondary companions of rapidly spinning pulsars in low-mass systems are expected to be white dwarfs. Observations of these white dwarfs are expected to provide critical clues to the evolution of magnetic fields of neutron stars and stellar evolution scenarios as well. We report new radio and optical observations of the 5.4 ms binary pulsar 1855+09. Using H I and CO observations we establish the visual extinction to the system to be about 1.5 mag. Recent timing observations by Ryba et al. have established that the companion or the secondary star has a mass of 0.22 $M_\odot$ and that the system is located more than 290 pc. We find only one star brighter than $R \sim 24.6$ that, on the basis of positional coincidence, can be plausibly the optical counterpart of the secondary star. The spectrum of this candidate is inconsistent with a low-mass main-sequence star. Neither is it a white dwarf because the spectroscopic distance modulus is inconsistent with the lower limit on distance obtained from timing observations. The true optical counterpart must be fainter than our detection limit: $R > 24.6$ and $I > 23.4$. Thus we conclude, as did Callanan et al., that the companion of PSR 1855+09 must be a low-mass cold white dwarf. At the nominal dispersion measure distance of 400 pc, all theoretical models predict a detectable white dwarf, inconsistent with our observations. However, at the larger distance of 800 pc, favored by the H I data, the upper limits are consistent with an old white dwarf. The inferred cooling age, while model-dependent, is comparable to 5×10^9 yr, the characteristic age of the pulsar. This result supports the hypothesis that magnetic field strengths of millisecond pulsars are essentially constant and that millisecond pulsars are long-lived objects. Further improvements in the parallax measurement and deeper images of the field are needed to understand the precise extent of the disagreement between different low-mass white dwarf cooling models and observations.

Subject headings: pulsars — radio sources: identifications — stars: binaries — stars: neutron — stars: white dwarfs

I. INTRODUCTION

Of the approximately 500 known pulsars in the disk, only 10 constitute the group of binary and/or millisecond pulsars. It is now believed by most workers, but not all, that such pulsars are the end products of X-ray binaries. Despite their small number, this group of pulsars offer considerable insight into the formation and evolution of neutron stars. Here we report radio and optical observations of one such pulsar: the 5.4 ms binary pulsar, 1855+09.

PSR 1855+09 was discovered during the course of a systematic survey carried out at the Arecibo Observatory by Segelstein et al. (1986). Timing observations quickly established that the system was in a binary system with a low-mass function: 5.2×10^{-3} $M_\odot$. Recent timing observations show that the inclination of the orbit is nearly 90° (Ryba, Taylor, and Stinebring 1990) and thus the mass of the secondary is 0.22 $M_\odot$, assuming the mass of the primary, i.e., the pulsar, is 1.4 $M_\odot$. Indeed, according to stellar evolution scenarios the companion is expected to be a low-mass white dwarf (see below). Given the proximity of this system (distance estimated to be 400 pc from the dispersion measure), further studies of the companion, especially at optical wavelengths, become attractive.

PSR 1855+09 with its low-mass function belongs to the class of low-mass binary pulsars (LMBPs; see Kulkarni and Narayan 1988). There are two scenarios for LMBPs (see van den Heuvel 1987, 1989; Verbunt 1990). In one model, the starting point is a binary system consisting of a low-mass star (~ 1 $M_\odot$) and a high-mass star ($\gtrsim 8$ $M_\odot$). Early on, the high-mass star evolves into a neutron star. At a later stage, the low-mass companion evolves the expands on a nuclear evolution time scale. Mass is transfered from the companion to the neutron star by Roche lobe overflow. During this phase, the system is visible as a bright X-ray source, the so-called low-mass X-ray binaries (LMXBs). The accreting matter carries with it the orbital angular momentum and hence the neutron star gradually gets spun up. The accretion phase probably lasts only a short time ($\sim 10^7$ yr; Kulkarni and Narayan 1988; Tavani 1990), over which time the orbit is circularized. At a later time, the secondary stops evolving and becomes a white dwarf. Accretion then ceases and the final result is a binary system consisting of a white dwarf and a rapidly rotating pulsar.

In the second model, the neutron star is replaced by a massive white dwarf. It is postulated that the accreting white dwarf is converted to a neutron star once its mass exceeds the Chandrashekar limit. This is the so-called "accretion induced

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collapse' origin of neutron stars. The subsequent evolution is then the same as in the previous model.

In either model, the white dwarf secondary is formed *after* the neutron star. Thus the age of the neutron star is necessarily an upper limit to the age of the white dwarf.

The study of pulsar–white-dwarf binaries is attractive because the ages of both the stars can be independently estimated. The pulsar age can be estimated from the so-called characteristic age, $\tau_p = P/(n-1)\dot{P}$, where n is the braking index; the standard assumption of $n = 3$ corresponds to pulsar energy loss by magnetic dipole radiation. Rawley, Taylor, and Davis (1988) find $\tau_p = 5 \times 10^9$ yr. In practice, $n \sim 2.7$ and thus the true characteristic ages of pulsars may be 15% higher than the standard value. If magnetic fields of millisecond pulsars do not decay, then τ_p is the time elapsed since the pulsar was spun up by accretion. However, τ_p is an upper limit to the true age of the pulsar and can be significantly higher that the true age of the pulsar if either (i) the current period of the pulsar is close to the initial period (i.e., the period of the pulsar at the end of the accretion phase) or (ii) the magnetic field decays, as has been observed for the ordinary slow pulsars.

The white dwarf age, τ_w, can be estimated from the application of theoretical cooling curves to the measured white dwarf luminosity (e.g., Mestel 1952; Iben and Tutukov 1984; Winget et al. 1987). (Note that under no circumstance τ_w is larger than τ_p. In either of the two scenarios discussed above, provided there is no field decay, the difference between the two ages is expected to be essentially zero since the birth of the white dwarf also results in the termination of the accretion and hence the spin up process.)

Using this path of reasoning, Kulkarni (1986), from a study of optical counterparts of two binary pulsars, concluded that magnetic field strengths of low magnetic field strength pulsars (e.g., the millisecond pulsars) is essentially constant. Additional support for this hypothesis was one of the motivations for the work reported here.

Observations of the companion are also needed to constrain stellar evolution scenarios. From the above discussion it is probably apparent that our understanding of the formation of millisecond pulsars is still quite rudimentary. While most workers believe that LMBPs evolve from LMXBs there are some fundamentally disconcerting inconsistencies (see Kulkarni and Narayan 1988). Direct evidence such as coherent millisecond pulsations from LMXBs has yet to be seen. Given this state, any additional observations of these systems, especially the companion, are likely to provide new constraints on the formation scenarios.

Given the small distance to PSR 1855+09, the companion white dwarf should be easily detectable with moden solid-state imaging detectors. Nonetheless, the optical candidate has been controversial. Wright and Loh (1986) reported a candidate as did Kulkarni (1987; finding chart in Kulkarni 1988). However, the finding chart given in the Wright and Loh paper is quite poor to the extent that it is not clear which star is the Wright. Loh candidate (see Callanan et al. 1989). Recently, Callanan et al. (1989) claim that to a limiting magnitude of $m_v \sim 25$ there is no optical source at the location of the pulsar.

Here we present additional observations of this field. We have extensively investigated the star closest to the nominal position of the pulsar (§ II). We have obtained independent and quite accurate measure of the total extinction from H I absorption and CO emission measurements toward the pulsar (§ III). This is particularly important since the pulsar is located in the Galactic plane (Galactic latitude $b = 3\overset{\circ}{.}1$) and extinction uncertainty will certainly cloud the interpretation. We also derive an independent estimate of distance from H I absorption data and conclude that the distance to the pulsar is twice that estimated from dispersion measure. Our optical spectroscopic and photometric data (§ IV) in conjunction with the recent parallax measurements of the pulsar (Ryba et al. 1990) rule out this star being the optical companion to the pulsar (§ V). Following Callanan et al. (1989), we argue that the true companion is fainter than our detection limit and that the white dwarf companion must be quite old, $\tau_w \sim \tau_p$ (§ VI). This supports the notion that magnetic field strengths of millisecond pulsars do not decay (§ VII). We conclude in § VII.

II. IMAGING AND ASTROMETRY

The initial imaging data were obtained at the Palomar 60 inch (1.52 m) and the Hale 200 inch (5.1 m) and the Kitt Peak 4 m telescopes in 1986 July and August, respectively. The astrometry was obtained in two steps. First, a set of stars, hereafter "secondary", were identified on a red CCD image of the field, obtained at the 60 inch Palomar telescope. The same set was identified on a direct yellow-sensitive photograph taken at epoch 1974.62 with the Lick 0.5 m Carnegie double astrograph, and the equatorial positions of these stars were obtained with respect to a set of 18 primary reference stars taken from the AGK3R catalog. These primary stars measured on a plate, taken originally for the Northern Proper Motion program (see Klemola, Jones, and Hanson 1987), define the position reference frame on the Lick plate. Since the field is very crowded (Fig. 1), the positions of the secondary stars on the Lick plate may be influenced by the near-blending of images. The estimated rms error is 0".3 in each coordinate. Most of the secondary stars on the Palomar Hale 200-inch images were saturated, and hence we chose a set of "tertiary" stars which were unsaturated in the Hale 200-inch images and

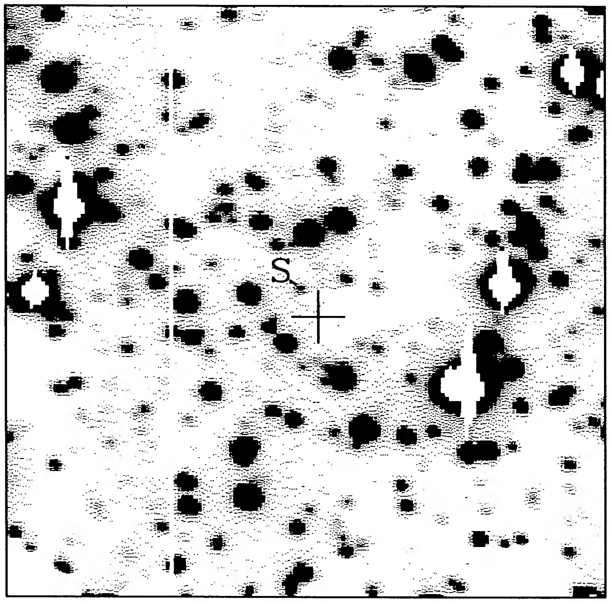

FIG. 1.—A section of an r band CCD image of the PSR 1855+09 field, obtained at Palomar. The field shown is 50" square, with north to the top, and east to the left. Note that the bright stars appear with white cores. This is due to the stretch chosen to clearly show S.

TABLE 1

PULSAR AND CANDIDATE POSITIONS

Source	α(1950.0)	δ(1950.0)
PSR 1855+09 (VLA)	$18^h55^m13^s.681 \pm 0.009$	$09°39'12''.8 \quad \pm 0.15$
PSR 1855+09 (Timing)	18 55 13.6834 ± 0.0006	09 39 13.278 ± 0.009
Star S	18 55 13.781 ± 0.04	09 39 15.20 ± 0.6

derived their equatorial positions using the frame defined by the secondary stars; the net rms in the positions of the tertiary stars is 0″.33 in each coordinate.

We repeated the same exercise using a plate of the Palomar Sky Survey and replacing the primary stars with the AGK3 in that region. There is a systematic difference of the positions of the secondary stars, in the sense POSS − Astrograph: $\Delta\alpha = 0.032$ s (=0″.44), $\Delta\delta = 0''.57$. We repeated the entire procedure with a *V* frame obtained from the 4 m telescope of Kitt Peak National Observatory. This was shallower than the Hale 200 inch frame and allowed us to bypass the use of the tertiary star. The same systematic difference was found. This difference is disturbing and suggests that the AGK3 is not reliable in this region of the sky. We will adopt a conservative rms uncertainty of 0″.7 in each coordinate.

In Table 1, we present the pulsar position(s) obtained from the VLA and timing observations (Segelstein et al. 1986) and the equatorial position of star S (Table 1 and Fig. 2), the star closest to the VLA position. The offsets of star S with the VLA position (in the sense star S − VLA) are $\Delta\alpha = 0.1$ s (=1″.44) and $\Delta\delta = 2''.4$. We note that star S is within the 3 σ error circle if the timing position is used. However, both VLA and the optical coordinate system are based on the same coordinate frame, the equatorial frame, whereas the pulsar timing system is with respect to the ecliptic frame. The differences between these two fundamental frames, at a level below 1″, are not yet understood. Given these uncertainties as well as the systematic uncertainty in the optical astrometry, we considered star S to be a plausible candidate, worthy of further observations.

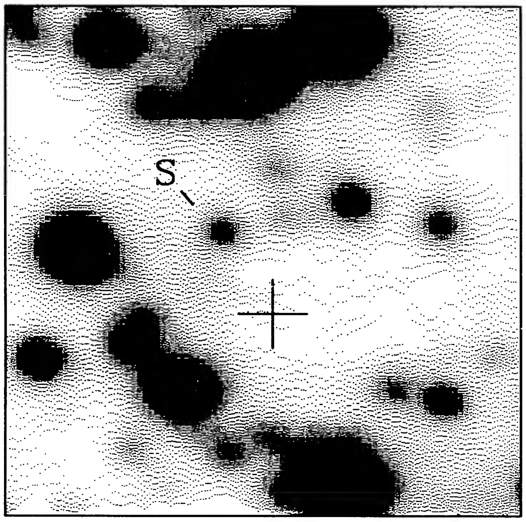

FIG. 2.—A zoom-in of a stack of *r*, *i*, and *z* CCD frames of the PSR 1855+09 field, obtained at Palomar. The field shown is 15″ square, with north to the top, and east to the left. The proposed counterpart (star S) and the nominal pulsar *VLA* position (*cross*) are marked. The length of each leg of the cross correspond to 1″.33. Star S is located 2″.4 north and 1″.4 east of the pulsar VLA position.

III. RADIO ABSORPTION, EXTINCTION, AND DISTANCE

Given the location of the pulsar (Galactic coordinates: $l = 42°.3$, $b = 3°.1$), it must be clear from the above discussion that an estimate of the extinction toward the pulsar is crucial for further discussion of the nature of the secondary companion. To this effect, radio observations were conducted in the 21 cm line of H I and the 2.6 mm line of CO to estimate the column density of the interstellar atomic and molecular component.

H I 21 cm absorption observations were done using the giant 305 m Arecibo radio telescope during a 4 day session starting 1987 October 30. At 21 cm wavelength, the mean flux density of the pulsar is a few mJy which is not sufficient for H I absorption observations. However, owing to interstellar scintillation, it is known that the flux density increases to ~10 mJy for tens of minutes (Rawley et al. 1988)—sufficiently bright for H I absorption experiments. Two banks of 128 lags, one for each sense of polarization, of the observatory's digital correlator were sampled at 700 μs. The resulting 2 × 128 array was summed by an array processor into one of 32 arays depending upon the phase of the sample with respect to the apparent pulsar period. The data were thus integrated for 100 s (off H I-line) and 3 × 300 s (on H I-line) to yield four arrays of size 32 × 256; this constituted one scan. The scans were processed in a manner identical to that described in Clifton et al. (1988). The scans were weighted by the continuum strength of the pulsar and added. The resulting absorption spectrum is shown in Figure 3. Owing to deep scintillations, only about 10% of the data were effectively used.

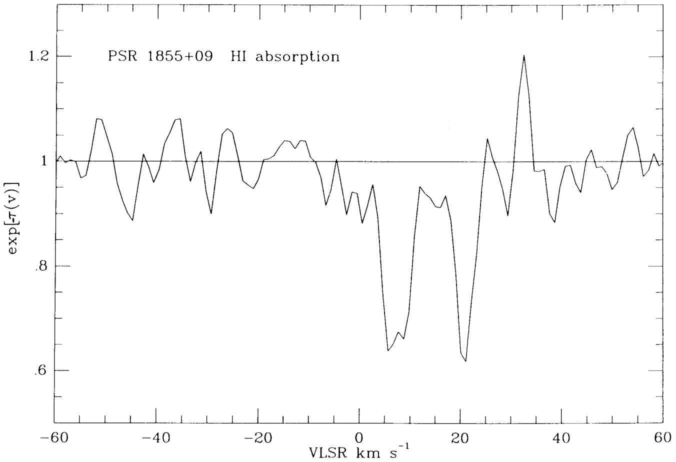

FIG. 3.—The 21 cm H I absorption spectrum of PSR 1855+09. The spectrum was obtained using Arecibo Observatory's 305 m telescope in a manner described in the text. The vertical axis is the fractional absorption of the pulsar continuum [$e^{-\tau(v)}$] and the horizontal axis is the local standard of rest of velocity (VLSR). The spectrum shown here has been Hanning smoothed from a spectrum with an original spectral resolution of 1.03 km s^{-1}.

Three prominent absorption features are seen at LSR velocities of 6, 8, and 21 km s^{-1}. The integrated optical depth, $V_\tau \equiv \int \tau(v)dv$ of the absorption spectrum is 5.9 ± 0.42 km s^{-1}. Using the procedure described by Crovisier (1981) and Kulkarni (1985), we deduce an atomic column density of 2.1×10^{21} cm^{-2}. To this we add 3.6×10^{19} cm^{-2} as contribution of the warm ionized medium assuming a mean density of 0.03 cm^{-3} pc (Reynolds 1989).

CO emission data were obtained by Robert Wilson using the AT&T Bell Laboratory 7 m telescope in 1988 December. A 20 minute integration spectrum with a 512×250 kHz filterbank is displayed in Figure 4. Emission features are seen at LSR velocities of 3 and 34 km s^{-1} with $\int T_A^* dv$ of 1.3 ± 0.3 K km s^{-1} and 1.7 ± 0.37 km s^{-1}, respectively. After correcting for the main beam efficiency these integrals translate to 4.7×10^{20} cm^{-2} and 6×10^{20} cm^{-2}, respectively (see Scoville and Sanders 1987 for details of this procedure). Application of the rotation curve yields a distance of 2.3 kpc for the 34 km s^{-1} feature. This distance is nearly a factor of 6 larger than the dispersion measure estimate (see below) and in addition no H I absorption features are seen with velocities greater than 21 km s^{-1}. Thus we conclude that the +34 km s^{-1} feature comes from a background molecular cloud in which case the total molecular column density to the pulsar is 9.4×10^{20} cm^{-2} of H atoms.

The total column density of interstellar material toward the pulsar is thus 3×10^{21} cm^{-2} which translates to an E_{B-V} of 0.5 or $A_v \sim 1.5$ with an uncertainty of about 20%.

A distance of 400 pc can be derived from the observed dispersion measure of 13.3 cm^{-3} pc and a model for the interstellar electron distribution. Such estimates are uncertain by no more than a factor of 2 (Lyne, Manchester, and Taylor 1985).

The H I absorption data provide an independent estimate of distance. Application of a flat rotation curve to the feature with the highest velocity (21 km s^{-1}) gives a kinematic distance of 1.4 kpc, inconsistent with the dispersion measure estimate. However, kinematic distance estimates are affected by random perturbations to the cloud velocities ($\sigma = 6$ km s^{-1}) and thus the uncertainty from this effect alone is ±0.4 kpc (1 σ). In addition, the observed number of H I absorption features and the inferred extinction are consistent with a lower distance estimate. We will adopt a distance of 800 pc as a compromise between the H I kinematical and dispersion measure estimates. We also note that with even this choice of distance the mean ISM density is 1.25 H atom cm^{-3}, somewhat less than the mean ISM density within 1 kpc of the Sun (Spitzer 1978, p. 17)—another argument against a distance estimate much higher than 0.8 kpc. This corresponds to a distance modulus $(m - M) = 9.5$ and using our estimate of A_V we find the distance modulus including extinction to be $(m - M)_{V,0} = 11$. The most dominant error is due to the uncertainty in the distance which from the above discussion can be as large as a factor of 2 or an error in the distance modulus of ±1.5.

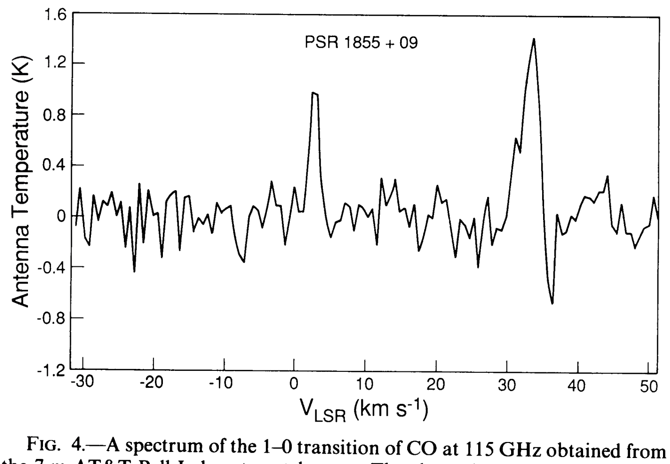

FIG. 4.—A spectrum of the 1–0 transition of CO at 115 GHz obtained from the 7 m AT&T Bell Laboratory telescope. The channel width is 0.65 km s^{-1}. As explained in the text, the +3 km s^{-1} feature is probably between us and the pulsar whereas the +34 s^{-1} feature is probably beyond the pulsar.

IV. PHOTOMETRY AND OPTICAL SPECTROSCOPY

Additional CCD imaging data for the *gri* photometry of the proposed counterpart, star S, were obtained using the 4-Shooter imaging/spectrograph camera (Gunn et al. 1987) on UT 1988 July 20, in photometric conditions. Multiple out-of-focus exposures of the standard star BD +28°4211 (Kent 1985) were used for calibration, and the photometry was done using the DAOPHOT package (Stetson 1987). We obtain the magnitudes $g = 23.35 \pm 0.25$, $r = 22.02 \pm 0.1$, and $i = 21.6 \pm 0.2$; aperture correction uncertainties contribute about half of the total errors. The colors are $(g - r) = 1.3 \pm 0.2$, and $(r - i) = 0.4 \pm 0.2$ (the aperture errors cancel). The *RI* photometry was done using the CFHT prime focus CCD images obtained on 1986 May 15 and 17. Exposures of the M92 standard field (Christian et al. 1985) were used to derive the color transformations and calibrate the data. We obtain for star S the following magnitudes $R = 22.25 \pm 0.3$, and $I = 21.6 \pm 0.3$. Again, uncertainties in the aperture corrections and random errors contribute about equally to the error bars. The color $(R - I)$ is 0.6 ± 0.4.

If we assume the interstellar reddening to correspond to $E_{B-V} = 0.5$ mag (§ III), and use the interpolation formulas by Seaton (1979), we derive the following corrected magnitudes and colors for star S: $g_0 = 21.6$, $r_0 = 20.8$, $i_0 = 20.6$, $(g - r)_0 = 0.85$, $(r - i)_0 = 0.25$, $R_0 = 21.1$, $I_0 = 20.9$, with the same uncertainties as above. Using the color transformations from Kent (1985) and J. Cohen (private communication), we derive from the corrected *gri* photometry, $V_0 = 21.5 \pm 0.3$ and $(B - V)_0 = 1.25 \pm 0.3$.

CCD spectra of star S were obtained at a Palomar 200 inch on the nights of UT 1988 July 18, using the Double Spectrograph (Oke and Gunn 1982), and UT 1988 July 20, using the 4-Shooter imaging camera/spectrograph. The spectra were calibrated using multiple exposures of the flux standards BD +28°2411, Feige 110, and HZ 44 (Oke 1974; Stone 1977). The low-resolution 4-Shooter spectrum is shown in Figure 5. The Double Spectograph data are in excellent agreement, but with a somewhat lower wavelength coverage and signal-to-noise ratio. No spectroscopic features, other than the telluric absorption, are seen in the data. The uncorrected spectroscopic magnitudes derived from our spectra are $V = 23.3 \pm 0.3$, and $R = 21.9 \pm 0.2$, in good agreement with the direct CCD measurements.

We also conducted a search for an Hα nebula on the Palomar 60-inch telescope on UT 1988 16 July using the same equipment that led to the discovery of a nebula around the binary pulsar 1957+20 (Kulkarni and Hester 1988). While our sensitivity was sufficient to detect a nebula similar to that around PSR 1957+20 we did not detect any nebula in the 1855+09 field. This is probably not too surprising given that

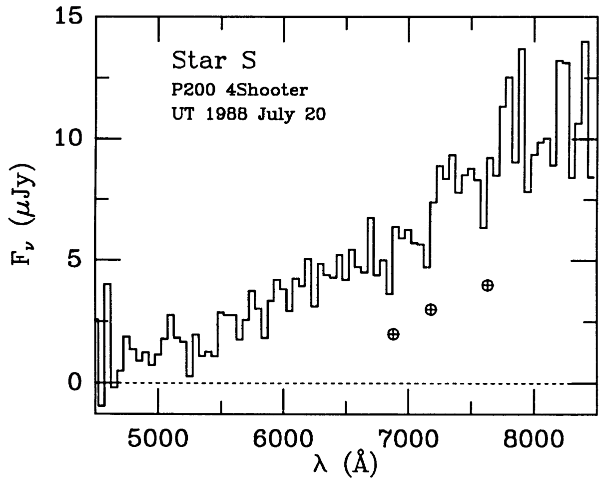

FIG. 5.—The 4-Shooter spectrum of star S, rebinned to 50 Å. The locations of the atmospheric absorption bands are indicated. The object shows no intrinsic emission or absorption within the limits of these data.

the rotational luminosity of PSR 1855+09 is a factor of 40 lower than that of PSR 1957+20.

V. NATURE OF STAR S

We have investigated the optical field around the 5.4 ms binary pulsar, 1855+09, with a view of detecting its companion which, according to stellar evolution models, is expected to be a low-mass white dwarf. Earlier in § II, we hypothesized that star S could be a plausible counterpart to this system. We now investigate whether this hypothesis is consistent with the data.

We fitted the blackbody curves filtered by the extinction curves to the spectrum of star S (Fig. 6). The best fit to the data (assuming $E_{B-V} = 0.5$ mag; see § III) is obtained for $T_e = 4000$ K, with maximum uncertainty of about 5%. This effective temperature is in good agreement with our color measurements.

Given the inferred mass of the companion (0.22 $M_\odot$), star S has to be either a low-mass main-sequence star or a white dwarf. The absolute visual magnitude of a 0.22 $M_\odot$ main-sequence star (an M type star) is ~12.5 (Allen 1976, p. 209) and hence an apparent visual magnitude of $23.5 + 5 \times \log(d/800 \text{ pc})$—consistent with our assumed distance of 800 pc. However, the effective temperature predicted for this star is about 2500 K which is in clear conflict with our blackbody fit to the spectrum and the measured colors. In addition, our spectra do not show the strong absorption bands, characteristic of M dwarfs. Thus, we conclude that star S cannot be a M dwarf.

The alternative possibility is that star S is a low-mass white dwarf. The radius of a 0.22 $M_\odot$ He white dwarf, at zero temperature, is 0.0193 $R_\odot$ (Hamada and Salpeter 1961). Assuming that the flux distribution can be approximated by a blackbody spectrum, we derive $M_V = 15.7$ for $T_e = 4000$ K. Since $V_0 \sim 21.6$ we obtain a distance modulus of 5.9 (~150 pc). This is at the low end of the distance estimated from dispersion measure. However, timing observations of the pulsar (Ryba et al. 1990) show that the parallax is less than 3.5 millarcsec (3 σ upper limit) or the distance has to be *greater* than 280 pc. Thus, it appears that star S cannot be a 0.22 $M_\odot$ white dwarf companion of PSR 1855+09.

Since the disagreement is based on a comparison of the spectroscopically derived distance modulus and the distance limit from pulsar parallax measurements, it is important to assess the uncertainties in the two estimates. From Figure 5, we adopt 10% as maximum error on the effective temperature. The maximum uncertainty in the extinction is about 20%. Thus it appears the spectroscopic distance can range from 90 pc to 200 pc. While it is possible that by stretching all estimates to the limit an agreement can be obtained between the spectroscopic distance and the parallax limit, we do note that the parallax limit is a strict 3 σ limit. Hence we conclude that star S is unlikely to be the 0.22 $M_\odot$ white dwarf companion of PSR 1855+09.

Thus the final alternative is that the true companion to the pulsar is star fainter than S, a conclusion already arrived at by Callanan et al. (1989). This possibility is discussed below.

VI. CONFRONTATION WITH WHITE DWARF COOLING MODELS

In the previous section we argued that the binary companion of PSR 1855+09 has to be a white dwarf. On the basis of stellar evolution scenarios (e.g., Savonije 1987), it can be argued that the composition of the white dwarf must be He. In addition, also according to stellar evolution scenarios since the

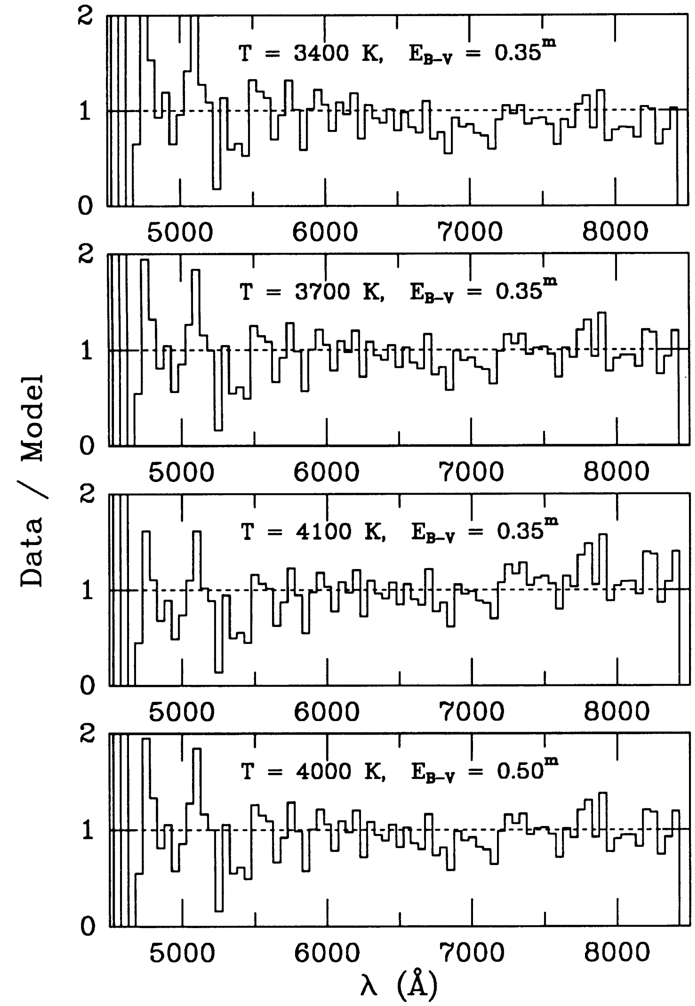

FIG. 6.—Blackbody fits to the spectrum shown in Fig. 5. The blackbody curves have been filtered with the interstellar extinction corresponding to $E_{B-V} = 0.35$ (the value derived assuming only extinction from atomic H I gas) and $E_{B-V} = 0.5$ (our best value; *bottom panel*). For $E_{B-V} = 0.5$, the best fit is obtained for $T_e \simeq 4000$ K.

white dwarf is formed *after* the neutron star (see § I), we note that the age of the white dwarf cannot exceed the characteristic age of the pulsar which has been measured to be 5×10^9 yr. In this section we confront models of white dwarf cooling with our optical data and see if the theoretical expectations are in accord with the data.

The detection limits are set by the sky background and can be straightforwardly estimated from our data. For this purpose we used 1200 s stacks of 4-Shooter images taken in various Gunn-Thuan *r*, *i*, *z* bands on the Hale 200-inch telescope taken on the night of 1986 August 10. In the vicinity of the nominal pulsar position, the sky rms in each pixel is 65 DN (digital number) and 129 DN for the Gunn *r* and *i* images. From this we find that the 3 σ uncertainty of the sum of pixels within a circle of 2 pixel radius is $r > 24.4$ and $i > 23.4$. Indeed, a closer inspection of the error circle reveal "objects" at this limiting magnitude or fainter. The brightest of these is located 0".4 west and 1".7 south of star S and has $r \sim 24.6 \pm 0.8$ and $i \sim 22.8 \pm 0.8$ (object not shown in Fig. 2, because of limitations in the dynamic range of hard-copy display). All this discussion, especially the magnitude of these faint objects, only proves (*a*) we are approaching confusion limit (not surprising given the low-latitude location of the pulsar field) and (*b*) our estimate of the limiting sensitivity is reasonable. For the purpose of discussion we will use these conservative limits, keeping in mind that the true companion may, in fact, have been detected at this limit. For the purpose of comparison with models we convert our limits to the Johnson system by scaling of photometry of star S, and find the limits to any optical counterpart of the 1855+09 system to be $R > 24.6$ and $I > 23.4$.

The comparison of the photometric limits to the models is not so straightforward since most cooling models are constructed for C-O or pure C white dwarfs of mass 0.6 $M_\odot$ or greater. However, the purported companion of PSR 1855+09 is a 0.22 $M_\odot$ pure He white dwarf with a He or possibly H envelope.

Theoretical models also usually quote bolometric luminosity. We assume that the emergent flux is adequately described by a blackbody spectrum and then estimate the Johnson *I*, *R*, and *V* magnitudes by evaluating the blackbody spectrum at 0.9 μm, 0.7 μm, and 0.55 μm, respectively. This is not a bad approximation as long as $T_e > 4000$ K (Kapranidis 1985). Using the zero point given in Johnson (1986) the corresponding absolute magnitudes M_I, M_R, and M_V are obtained. To these absolute magnitudes we add the following extinction corrections: 0.72(*I*), 1.15(*R*), 1.6(*V*), and a distance modulus of 9.5 to derive the predicted apparent magnitudes (Table 2).

Simple application of the *scaling* of Mestel's (1952) cooling formula show that for a given cooling time, τ_p, the cooling luminosity scales as $MA^{-7/5}$ where *M* is the mass of the white dwarf and *A* is the mean atomic number of the interior. Thus, for a given cooling time, a pure He ($A = 4$) white dwarf of 0.22 $M_\odot$ is expected to be 1.86 more luminous than a 0.6 $M_\odot$ pure carbon ($A = 12$) white dwarf.

We first examine the model of Winget et al. (1987) according to which the luminosity of a 0.4 $M_\odot$ carbon white dwarf is $L_C(1) = 5.6 \times 10^{-4}\ L_\odot$ and $L_C(5) = 5.3 \times 10^{-5}\ L_\odot$ where the values in the parenthesis refer to the cooling age, τ_w of the white dwarf in units of 10^9 yr; the model assumes no H or He envelope, a somewhat unrealistic assumption. Scaling this to a 0.22 $M_\odot$ He white dwarf the predicted luminosities are $L(1) = 1.4 \times 10^{-3}\ L_\odot$ and $L(5) = 1.4 \times 10^{-4}\ L_\odot$. The corresponding blackbody surface temperatures are $T_e(1) = 8000$ K and $T_e(5) = 4500$ K.

Next we consider the model of Iben and Tutukov (1986) who have explicitly considered the evolution of a 0.3 $M_\odot$ pure He white dwarf in a binary system. This is our choice model because it is most closely applicable to the object under discussion. These authors find the very surprising result that such a white dwarf cools identically to a 0.6 $M_\odot$ pure C white dwarf (Iben and Tutukov 1984). From Figure 2 of Iben and Tutukov (1986) we find $L_{\rm He}(1) = 1.4 \times 10^{-3}\ L_\odot$ and $L_{\rm He}(5) = 1.1 \times 10^{-4}\ L_\odot$. Decreasing these estimates by the ratio of the masses, $0.22/0.3 = 0.73$ we find the expected luminosities are $L(1) = 1.0 \times 10^{-3}\ L_\odot$ and $L(5) = 0.8 \times 10^{-4}\ L_\odot$, significantly lower than that predicted by the Winget et al. model. The corresponding effective temperatures are $T_e(1) = 7400$ K and $T_e(5) = 4000$ K.

The predicted apparent magnitudes for both these models with $\tau_w = 10^9$ yr and $\tau_w = 5 \times 10^9$ are given in Table 2. With both the Winget et al. model and the Iben and Tutukov model, our 3 σ upper limits, $R > 24.6$ and $I > 23.4$, are certainly inconsistent with a cooling age of 10^9 yr. At $\tau_w = 5 \times 10^9$ yr, our limits are barely consistent with the Winget et al. model and certainly consistent with the Iben and Tutukov model. The Iben and Tutukov model requires that $\tau_w \gtrsim 4 \times 10^9$ yr for $d = 800$ pc. Thus we can conclude that the white dwarf in the 1855+09 system has an age comparable to τ_c. Of course, this conclusion is dependent upon the assumed distance. If the pulsar is located at a distance of 1.4 kpc, using the Iben and Tutukov model we find $\tau_w \gtrsim 2.3 \times 10^9$ yr.

To summarize, our 3 σ upper limits are consistent with the predictions of theoretical cooling models. Perhaps we are even seeing the white dwarf at the limit of our CCD frame. However, if the pulsar is located at a distance of 400 pc, the nominal dispersion measure estimate, then the model predictions are inconsistent with the observations in the sense that the models predict hotter and more luminous white dwarfs than allowed by the observations. A more precise statement of the disagreement between theory and observations would need significant improvement of the pulsar parallax measurement and higher quality imaging data.

Parenthetically we note that our data are in strong disagreement with one of earliest model of low-mass He white dwarfs in binary systems (Webbink 1975). We use the 0.25 $M_\odot$ model of Webbink (as shown in Fig. 2 of Iben and Tutukov 1986) and find that the predicted effective temperatures are $T_e(1) = 1.5 \times 10^4$ K and $T_e(5) = 9 \times 10^3$ K. There is no doubt that we would have detected such a hot white dwarf even if it were located at 2.5 kpc (which, on the basis of the lack of H I absorption features at large positive velocities, is certainly unlikely; see § III).

All along we have implicitly assumed that the white dwarf

TABLE 2

PREDICTED MAGNITUDES[a]

Model	$\tau_w(10^9$ yr)	M_I	M_R	M_V	*I*	*R*	*V*
W[b]	1	11.70	11.81	12.08	21.9	22.5	23.2
IT[c]	1	11.90	12.05	12.38	22.1	22.7	23.5
W[b]	5	13.52	14.05	14.89	23.8	24.7	26.0
IT[c]	5	14.01	14.68	15.68	24.2	25.3	26.8

[a] Distance assumed to be 800 pc and $A_v = 1.5$.

[b] Winget et al. 1987.

[c] Iben and Tutukov 1986.

companion cools without being significantly affected by radiation (photons and particles) from the pulsar. This is a secure assumption since the amount of the bolometric power of the pulsar that is incident on the white dwarf is $6 \times 10^{-6}\ L_\odot$ which, given the above discussion, is negligible compared to the cooling luminosity.

VII. DISCUSSION AND CONCLUSION

We have undertaken a radio and optical study of the binary, millisecond pulsar 1855+09. Timing observations have established that the companion is a star with a mass of 0.22 $M_\odot$. Using radio data (H I and CO) we show that the interstellar extinction toward this system is $E_{B-V} = 0.5$ with an uncertainty of 20%. Establishing this value is important since the pulsar is located in the Galactic plane and uncertainties in extinction have clouded discussions in previous studies. We also found some evidence that the pulsar may be located as much as 800 pc from the Sun, about twice the standard estimate derived from the dispersion measure data. Optical photometric and spectroscopic observations were carried out for star S (Fig. 2). The optical data rule out star S as being a main-sequence star of 0.22 $M_\odot$ mass. Assuming that star S is a white dwarf companion is also not compatible with the optical data. In particular, the lower limit on the distance (parallax measurement derived from pulsar timing observations of Ryba et al. 1990) is significantly larger than the spectroscopically derived distance estimate. Thus we conclude that star S is an unrelated star.

The small extinction toward the system and the absence of an optically detectable companion mean that the secondary star has to be cold and hence a faint white dwarf. In the framework of models of white dwarf cooling, the lack of optical detection of the white dwarf clearly indicates that it is certainly older than 10^9 yr. From considerations of stellar evolution models we argue that the cooling age of the white dwarf can only be smaller than 5×10^9 yr, the characteristic age of the pulsar. Our 3 σ upper limit to a stellar companion at r and i bands is consistent with the predictions of the cooling models for a white dwarf with a cooling age comparable to the characteristic age of the pulsar. Thus we conclude that magnetic field strengths of PSR 1855+09, a low magnetic field strength, millisecond pulsar has been essentially constant for the last $\lesssim 5$ billion years.

With improved distance estimate to the system (from pulsar timing) and deeper imaging (in good seeing), we should be in a position to compare and discriminate different white dwarf cooling models. The current data can rule out one of the earliest models of white dwarf cooling and there is a hint that a more recent model (Winget et al. 1987) perhaps predicts higher luminosity than is observed. The great attraction here is that these white dwarfs are unlike most field white dwarfs. Only in such rare binary systems does nature produce low-mass He white dwarfs. Clearly, further observational pursuit of such systems will be well worth the effort.

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