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Optical spectroscopy and photometry of the companion of the bright millisecond pulsar J 0437–4715*

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Abstract. Absolute astrometry on two Schmidt sky survey plates and relative astrometry in a new CCD image identify a faint star as the optical counterpart of the recently discovered nearby millisecond and low-mass binary pulsar PSR J 0437–4715. The star lies within 0.2±0.4 arcsec of the pulsar's radio position and has a proper motion of 0.11±0.04 arcsec yr^{-1}. Spectra show the star to be a DC-type degenerate red star with an approximate temperature of 4000 K. The absolute luminosity of such a star and its apparent *V* magnitude of 20.6 agree well with the radio distance based on the dispersion measure. Depending on assumptions made about the luminosity, the most probable range for the cooling age of the companion is 0.9-3.7 Gyr, i.e. longer than the published spin-down age of 0.8 Gyr of the pulsar.

If the latter age is correct, the difference potentially raises questions about the spin-down mechanism of millisecond pulsars, which may not be dominated by the braking effect of the magnetic dipole. The relatively old age would also support previous suggestions that the decay of pulsar magnetic fields asymptotically terminates at a level of 10^8-10^9 G. It might furthermore reduce the discrepancy between the presently observed numbers of low-mass binary pulsars and low-mass X-ray binaries which are thought to be the progenitors of the former. On the other hand, more recent radio observations suggest a dynamical age of the pulsar of 2 Gyr which agrees well with the cooling age of its companion.

Key words: binaries: spectroscopic – stars: low mass – pulsars: individual: PSR J 0437–4715 – stars: white dwarfs

1. Introduction

It has been proposed (for an early review see van den Heuvel 1987) that the binary pulsars which are not members of globular clusters (where binary formation by capture plays an important role; for other possible differences see Chen et al. 1993) can be divided into two categories. Members of the so-called PSR 1913+16 class are characterized by (a) comparatively short orbital periods, (b) companion masses of about one solar mass or even more, and (c) often very eccentric orbits. The prototype of the other class is PSR 1953+29 whose members have (a) longer orbital periods, (b) probable companion masses of less than 0.5 solar masses, and (c) circular orbits. Detailed arguments have been presented (see Bhattacharya & van den Heuvel 1991 and references therein) that identify the former group with massive X-ray binaries and the latter with low-mass X-ray binaries (LMXB's; although the neutron star may have formed in different ways, cf. Srinivasan & Bhattacharya 1987 and Verbunt 1990).

Even though this idea is still based on just a handful of members in either group, it has been widely accepted. However, the model is partly lacking direct observational constraints. Very little is known especially about the companions of binary pulsars. The masses are estimated on the basis of mass functions derived from timing observations. Deep imaging has in a number of cases failed to detect the companion (e.g., Kulkarni et al. 1991 but see also Sect. 3.4). Only for a few companions could photometry establish directly that they are subluminous stars, probably white dwarfs (e.g., Kulkarni 1986). An as yet unsolved problem is the number of low-mass binary radio pulsars (LMBP's) which seems to exceed the number of low-mass X-ray binaries by a factor which at short orbital periods may well be an order of magnitude or more (Kulkarni & Narayan 1988).

The recent discovery of a bright millisecond pulsar (Johnston et al. 1993), which according to its dispersion measure may be closer to the Earth (150 pc) than any other known LMBP, offers a new opportunity to constrain models more strongly. PSR J 0437–4715 appears to fall into the second category defined above as the mass of its companion is 0.14/sin i $M_\odot$ and the eccentricity is 2×10^{-5} (Johnston et al. 1993). Only the orbital

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* Based on observations obtained at the European Southern Observatory on La Silla, Chile

period of 5.74 days is clearly on the short side. Pulsed radiation has also been detected in soft X-rays (Becker et al. 1993).

In the above model, the neutron star of PSR J 0437–4715 would have formed from either a more massive star in a type II supernova event (cf. van den Heuvel 1987) or from a white dwarf which after mass transfer from the companion underwent a collapse when its mass exceeded the Chandrasekhar limit (Nomoto 1987; Srinivasan & Bhattacharya 1987; Verbunt 1990). Mass transfer from the companion would in any case have spun up the neutron star to its present rotation rate of one turn every 5.76 ms. A necessary condition for such short periods is that the pulsar's original magnetic field of order 10^{12} G had previously decayed by a factor $\sim$ 1000 for which the time scale is of order 10^7 yr.

On the other hand, in order to be consistent with the presently observed number of LMBP's, the magnetic field of a millisecond pulsar must not continue to decay at the same rate (Kulkarni & Narayan 1988). There are indications that the magnetic fields of LMBP's reach a final plateau level of 10^8-10^9 G (Kulkarni 1986; van den Heuvel et al. 1986). The measured magnetic field strength of PSR J 0437–4715 is 8.3×10^8 G (Johnston et al. 1993). The age of some of the companions and the relatively large number of LMBP's (Kulkarni & Narayan 1988) suggest that the lifetime of this plateau could be of the order of the spin-down age, $P/2\dot{P}$, of the pulsar. This so-called characteristic age of PSR J 0437–4715 is 7.6×10^8 yr (Johnston et al. 1993).

Our optical photometry and spectroscopy reported below of the apparent companion of PSR J 0437–4715 are in general agreement with the above sketched picture but also add important new details.

2. Observations and data reduction

2.1. Astrometry

Astrometry was performed on a glass copy of a plate which in the course of the ESO/SERC R-band survey had been exposed on Nov. 17/18, 1982 with the ESO Schmidt telescope on La Silla. The positions of 24 stars from the PPM catalogue (Bastian & Röser 1990) were measured on ESO's Optronics S3000 machine. The measurements were repeated on a second day. A bi-variate, second-order polynomial fitted the measurements with an r.m.s. of between 0.21" and 0.28" in both right ascension and declination. Within 10" of the pulsar only one faint point source is visible. It was already referred to by Becker et al. (1993) and Johnston et al. (1993). The results of our measurements for this star are compiled in Table 1 and compared to the radio position of the pulsar (Johnston et al. 1993).

With a third-order polynomial the formal errors go down by 10% in both α and δ, but the position of the target changes only minimally. Since the object is positioned close to the southern edge of the plate, and the distribution of the standard stars is not optimal, the solution with the second-order polynomial should anyway be preferred. A general source of a systematic error is probably that the target is much redder than are most of the standard stars used and very much fainter than all of them.

Table 1. Astrometric positions (J2000.0) of the pulsar and its optical candidate counterpart. The radio position is the one of Johnston et al. (1993). The optical measurements were made on glass copies of the original plates; the errors are the standard deviations of a second-order, bi-variate polynomial fitted to 24 standard stars. The results given are the mean of two independent measurements which differed by less than one standard deviation. How the NTT measurements were performed is described in Sect. 2.1

Source	Epoch	$\alpha_{J2000.0}$	$\delta_{J2000.0}$
Radio	1992.62	04h 37m 15.72 s	–47° 15' 8.2"
		±0.02 s	±0.2"
ESO R-Survey	1982.88	15.62 s	7.8"
		±0.03 s	±0.3"
SERC J-Survey	1983.87	15.60 s	7.6"
		±0.02 s	±0.3"
NTT	1993.17	15.71 s	8.0"
		±0.03 s	±0.3 "

We have followed the same procedure for a glass copy of the UKSTU J-survey plate of the pulsar field. The results are also included in Table 1.

Finally, we have measured the positions of 33 point sources (some of which may be faint galaxies) and the pulsar candidate counterpart in a 2-minute exposure which had been obtained with EMMI at the NTT as an acquisition frame for our spectroscopy (see Sect. 2.2). No filter had been used, and the exposure is roughly 2 magnitudes deeper than either Schmidt plate available to us. We have chosen this image because with its relatively large field of 7.5 arcminutes squared it shows more and more evenly distributed objects which can be used as reference sources than the other direct CCD images obtained by us (Sect. 2.3).

The same objects were measured on the two Schmidt plates. A linear, bi-variate regression analysis between the two photographic datasets showed them to be consistent with each other to within better than ±0.15". The same technique applied to the EMMI data also yielded an r.m.s. scatter of 0.15" for the 33 reference sources when paired with each of the two plates. The only source with outstanding deviations from this (mainly in right ascension) was the pulsar with residuals of 1.0" in α and 0.5" in δ in the sense that the offset from the radio position is reduced from 1.2"±0.4" to 0.2"±0.4" (Table 1).

The difference between the various optical positions implies a proper motion of 0.11 $\pm$ 0.04" per year. At the distance of 150 pc suggested by the dispersion measure (Johnston et al. 1993), this corresponds to a tangential velocity of $78 \pm 29\,\mathrm{km\,s^{-1}}$.

Because of the 6-7 σ proper motion and the near-identity (to within the errors) of the radio and the NTT position, we conclude that the star identified by us is the optical counterpart of PSR J 0437–4715.

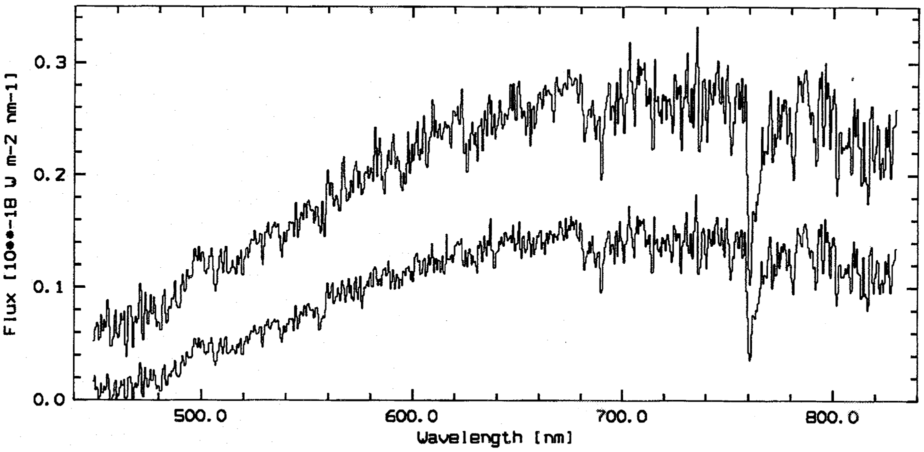

Fig. 1. Composite spectrum of the companion to PSR J 0437–4715. The same spectrum with corrections for slit losses and interstellar reddening corresponding to $E(B-V) = 0.07$ mag applied (see Sect. 2.2 for details) is plotted with a vertical offset of $+0.05\times10^{-18}$ W m^{-2} nm^{-1}. At 690 and 760 nm, respectively, the telluric A- and B-band can be seen

2.2. Spectroscopy

A total of five one-hour exposures was taken of the source identified in the previous section. The first two were obtained on March 4, 1993 with EMMI (Dekker et al. 1986; Melnick et al. 1992) at the 3.5-m New Technology Telescope (NTT) on La Silla, the third one a day later. A grism with 300 grooves/mm (EMMI No. 2) and a Thompson CCD of 1024 19-μ pixels (ESO No. 18) gave a useful spectral response between 500 and 835 nm, and the spectrum was sampled with 0.46 nm/pixel. Two more spectra were exposed on March 15, 1993 with EFOSC1 (Buzzoni et al. 1984) attached to ESO's 3.6-m telescope. The detector was a Tektronix CCD with 512 pixels of 27μ each (ESO No. 26). With the B300 grism the spectral coverage was from 380 to 695 nm at a sampling of 0.62 nm/pixel. In all cases the slit width was set to 1.5 arcsec.

The reduction of the observations followed standard procedures. Since the spectra were taken close to full moon, special care was exercised with the subtraction of the night sky spectrum. The procedure adopted was to heavily smooth the background with a median filter running perpendicularly to the dispersion direction. This filtered image is a very good approximation to the background at the position of the stellar spectrum. Backgound correction therefore consists of subtracting this filtered spectrum.

The EFOSC spectra and the first 2 EMMI spectra were flux calibrated by comparison with a standard star. The EMMI spectra were nearly indistinguishable from one another whereas the EFOSC spectra showed somewhat lower flux levels which were also different from each other. There is no obvious explanation for these differences which, however, do not affect much the flux *distribution*. We have scaled them up (by a wavelength-independent constant) to match the mean flux level of the EMMI spectra. The same was done for the third EMMI spectrum for which no separate standard star spectrum could be obtained whereas the detector gain was changed because the night had to be shared with another observer's program.

For each spectrum we have computed the slit losses under the assumption that the object was perfectly centered on the slit, the effective seeing was given by the spatial profile of the spectra, and the effective wavelength at which the autoguider worked was 550 nm. Depending on hour angle, slit position angle, and wavelength, the correction factors were between 15 and 45%.

We have made a combined spectrum using only the EFOSC spectra below 520 nm, all five from 520 to 680 nm, and beyond 680 nm the EMMI spectra only. It was corrected for interstellar extinction by means of a standard Galactic reddening law (Savage & Mathis 1979) and $E(B-V) = 0.07$ mag (Sect. 2.3). The final result was obtained by replacing all spikes, which deviate by more than 10% from the median of the 4 nearest neighbouring pixels of initially 0.2 nm, with that median value and resampling to a step of 0.5 nm. In the range 520 to 680 nm the spectrum has a S/N of 11.4. It is shown in Fig. 1 both with and without corrections for slit losses and interstellar reddening applied. The slit loss corrections reduced the S/N (measured between 520 and 680 nm) from 12.7 to 11.4 because although spectra with large losses had a lower S/N, they now attain higher weight because of the corrections.

2.3. Photometry

CCD photometry was obtained with EFOSC2 at the 2.2-m MPG telescope, SUSI (Melnick et al. 1992) at the New Technology Telescope, and EFOSC1 (Buzzoni et al. 1984) at the 3.6-m telescope, all at ESO's La Silla observatory. The exposure times for the pulsar field ranged from 2 to 15 minutes. Part of a 15-minute I-filter exposure taken with the NTT is reproduced in Fig. 2.

The sky conditions were not unambiguously photometric during the night at the 2.2-m. With the 3.6-m telescope, also a photometric standard star was observed (defocussed to increase the S/N and to reduce shutter timing errors). The observations with the other two telescopes were reduced with respect to these measurements. The photometry of the pulsar was made relative to two nearby comparison stars, one of which is much redder than the pulsar. The results are listed in Table 2. The single largest source of error are the mean extinction coefficients used because the dust ejected during the eruption of Mt. Pinatubo on the Philippines still caused significant extinction variations from night to night and even during a night. From our observations, no significant variability of the companion with orbital phase can be deduced.

Table 2. Photometry of the optical counterpart of PSR J 0437–4715

	Telescope	Date	V	$B-V$	$V-R$	$R-I$
	2.2 m	26-02-1993	20.85		0.78	0.57
			±0.03		±0.01	±0.01
	NTT	01-03-1993	20.85		0.75	0.58
			±0.02		±0.02	±0.02
	3.6 m	15-03-1993	20.81	1.35	0.77	0.53
			±0.01	±0.06	±0.01	0.02
Mean			20.84	1.35	0.77	0.56
			±0.02	±0.06	±0.01	±0.02
Dereddened			20.62	1.28	0.71	0.51
			±0.10	±0.06	±0.03	±0.04

The measurements were corrected for interstellar extinction (Table 2) by assuming a distance of 150 pc (Johnston et al. 1993), a corresponding colour excess of $E(B-V)=+0.07$ mag (Knude 1979), and a standard Galactic extinction law (Savage & Mathis 1979).

3. Discussion

3.1. The temperature of the companion

From the lack of eclipses Johnston et al. (1993) already concluded that the companion to PSR J 0437–4715 must be a compact object. The optical spectrum is obviously due to a very cool source and reminiscent of DC-type white dwarf spectra. In similar objects, Ruiz et al. (1989) detected a broad (∼20 nm), shallow absorption line near 660 nm which is still unidentified. Even this feature is not clearly detected in PSR J 0437–4715.

Kapranidis (1985) has computed monochromatic fluxes and colours for cool degenerate stars with a pure helium atmosphere. As Kapranidis & Liebert (1986) have shown, the assumption of a helium-dominated atmosphere is reasonable for DC stars. For a $V-I$ index of 1.2 as observed in PSR J 0437–4715, these models give an effective temperature of about 4750 K. By contrast, for the $B-V$ index of 1.28, Kapranidis' models yield $T_{\rm eff}=3500$ K.

Comparison of the monochromatic fluxes of the $T_{\rm eff}$ = 4750 K model with the observed flux distribution of PSR J 0437–4715 shows a rather poor match. Only for temperatures around 4000 K is the peak of the flux distribution at about the right wavelength. However, there are considerable flux deficits with respect to the model towards both blue and red wavelengths. Other published spectra of very cool degenerate stars (Ruiz et al. 1989; Hintzen et al. 1989) do not extend far enough towards long wavelengths to permit a similar conclusion to be drawn for them. But for some stars one may wonder whether their flux distribution is also more sharply peaked than Kapranidis' models or black body flux distributions. We suspect that this anomaly affects the $V-I$ index which is formed as the ratio of measurements on either side of the peak of the flux distribution whereas $B-V$ measures the slope on the blue side only. Therefore we adopt an effective temperature of 4000 K. In the extension towards low temperatures of the classification scheme proposed by Sion et al. (1983) this corresponds to a spectral type of DC13.

There is no doubt that the companion of PSR J 0437–4715 is as red as any of the stars discussed by Ruiz et al. (1989) and Hintzen et al. (1989). With the possible exception of ER8, its flux distribution appears to peak at least 50 nm longward, and also its $(B-V)$ index is comparable. Accordingly, the companion of PSR J 0437–4715 is one of the coolest and, therefore, least luminous degenerate stars known.

3.2. The distance

Hintzen et al. (1989) argue that the absolute visual magnitude M_V of such a cool field white dwarf is about +16 (see also Liebert et al. 1988 and Wood 1992). However, the typical mass of field white dwarfs is 0.6 $M_\odot$ (Weidemann & Koester 1984; Weidemann 1987) whereas for the one of the companion to PSR J 0437–4715 about 0.2 $M_\odot$ has to be assumed. From the mass-radius relation (in solar units) for white dwarfs (Nauenberg 1972):

$$R(M)=\frac{0.0225}{\mu_e}\left[\left(\frac{M}{M_3}\right)^{-2/3}-\left(\frac{M}{M_3}\right)^{2/3}\right]^{1/2} \qquad (1)$$

where μ_e is the mean molecular weight per electron, and $M_3=5.816/\mu_e^2\,M_\odot$ is the upper mass limit for white dwarfs, one infers (adopting μ_e=2) a radius of 0.021 $R_\odot$ rather than 0.012 $R_\odot$ for the more massive field stars and accordingly a corrected absolute magnitude of +14.9. Together with the apparent V magnitude of 20.6, this would place PSR J 0437–4715 at a distance of 138 pc. This value is in good agreement with the estimate of 150 pc derived from the dispersion measure (Johnston et al. 1993). Lyne et al. (1985) found that the error of dispersion measure distances is typically a factor 1.5 and occasionally reaches a factor 2.

Further constraints can be put on the distance by exploring the effective temperature-radius parameter space. $T_{\rm eff}=3750$ K and $R=0.015\,R_\odot$ (Shipman 1979; Kapranidis 1985) yield $L=10^{-4.4}\,L_\odot$ and, with a bolometric correction taken from the work of Liebert et al. (1988), $M_V=16.6$ mag which corresponds to $d=65$ pc. This luminosity is close to the cut-off found (Winget

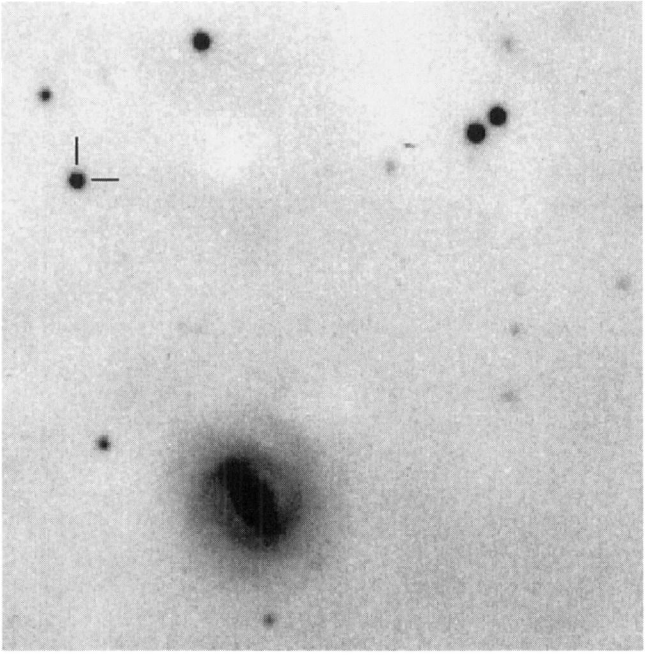

Fig. 2. Finding chart of PSR J 0437–4715. The 15-minute exposure was taken with the 3.5-m NTT and SUSI through an I-filter. The seeing was 0.75 arcsec, and the field shown measures 50×50 arcsec^2. North is up, east to the left. The pulsar (marked) is not in the center because over more than 35 arcseconds to both the north and the east no other sources are visible

et al. 1987; Liebert et al. 1988; Wood 1992) in the luminosity function of single degenerate stars. Sixty-five parsecs should therefore be a conservative lower limit, with some uncertainty due to the membership of the star in a close binary with a special evolutionary history. An upper limit of $d = 160$ pc to the distance is obtained with $T_{\rm eff} = 4500$ K and $R = 0.025\,R_\odot$ which is equivalent to $L = 10^{-3.6}\,L_\odot$.

In the above calculations, it has been assumed that the contribution of the pulsar to the visual flux is negligible. Circumstancial evidence in support of this assumption is the peakedness of the optical flux distribution which any additional component would tend to dilute. Since the pulsar's period is accurately known, high-speed photometry should provide an unambiguous estimate of the contribution of pulsed radiation to the total flux. Any such contribution would increase all distance estimates made.

3.3. The age of the white dwarf

For luminosities of $10^{-3.6}\,L_\odot$ and $10^{-4.4}\,L_\odot$, Wood's (1992, see also Winget et al. 1987) age-luminosity relations for a $0.4\,M_\odot$ star with a helium atmosphere give an age of 2.0 and 6.5 Gyr, respectively. If the mass of the layer is increased from $10^{-4}\,M_\star$ to $10^{-3}\,M_\star$, the age is reduced by about 0.5 Gyr. These numbers differ only little for stars with a carbon, oxygen or mixed carbon-oxygen core. However, by contrast, the companion of PSR J 0437–4715 is probably a helium star (cf. Pylyser & Savonije 1988) and has a mass of only about $0.2\,M_\odot$. Since no specific calculations of the cooling age of such a star are available, it has to be inferred from a suitable scaling law.

According to elementary theory, the cooling time, τ, of a white dwarf with a core composition of atomic number A and an atmospheric composition characterized by hydrogen abundance X, metal abundance Z, and mean molecular weight μ is given by the relation (cf. Eqs. 4.2.7 and 4.2.8 in Shapiro & Teukolsky 1983):

$$\begin{aligned}\tau &\propto \frac{Z^{2/7}(1+X)^{2/7}}{A}\left(\frac{\mu_e^2}{\mu}\right)^{2/7}\left(\frac{L}{M}\right)^{-5/7}\\ &\propto \frac{Z^{2/7}(1+X)^{2/7}}{A}\left(\frac{M}{R^2}\right)^{5/7} T_{\rm eff}^{-20/7} \qquad (2)\end{aligned}$$

where the second proportionality follows from the Stefan-Boltzmann law. Eqs. (1) and (2) can be used to ratio the cooling time of a $0.2\,M_\odot$ helium white dwarf (A=4) to the cooling time computed by Wood for a $0.4\,M_\odot$ carbon-oxygen white dwarf (A=14). Note that the effective temperature does not enter into the desired comparison because it is supposed to be the same for the two stars. The hydrogen abundances are also similar. Wood's models are based on $X = 0$. Since we do not detect Balmer lines in the companion of PSR J 0437–4715, $X = 0$ must be a good approximation, and the weak dependence of the cooling time on X renders any residual differences fully negligible for our purposes.

The metals observed in some white dwarfs are generally attributed to accretion from the interstellar medium. Model atmosphere analyses of a number of cool DC stars by Koester et al. (1982) find only traces of carbon at a level of $10^{-7} - 10^{-6}$ relative to helium. In a cool white dwarf with very strong lines in the optical spectrum, Kapranidis & Liebert (1986) report an abundance of heavy elements – especially calcium – of the order 10^{-2} of the solar ratio of metals to helium. Because our spectrum of PSR J 0437–4715 is featureless, a metallicity of $Z = 0.001$, as assumed in Wood's models, would therefore be a relatively extreme upper limit. For a more realistic value of $Z = 10^{-6}$, Eq. 2 leads to a revision of the range of cooling times from 2.0-6.5 Gyr to 0.4-1.4 Gyr and, for a total mass of the helium layer of the CO reference star, to 0.3-1.3 Gyr.

A more elaborate approach has been followed by Wood (1992) who reports on numerical experiments which were carried out in connection with his model calculations. According to these tests, the decrease in age with the radiative opacity of the envelope is less steep than implied by Eq. 2. For a $0.6\,M_\odot$ DB star with $L = 10^{-4.5} L_\odot$ the age differences resulting from the variation of the opacity by an order of magnitude amounted to ±1.4 Gyr. This corresponds to roughly ±15%, whereas from Eq. 2 a reduction in age by almost 50% is implied for the same decrease in opacity. If the factor derived from Wood's analysis can be applied over 3 orders of magnitude in Z and to stars of masses and luminosities appropriate for the present case, one may replace the opacity dependent factors in Eq. 2 with the one resulting from this assumption. In this way, ages ranging from 1.2 to 3.9 Gyr are derived. If the comparison is with a CO white dwarf with a thicker helium layer (cf. above), it becomes 0.9-3.7 Gyr.

Obviously, the uncertainties of the cooling age of the companion of PSR J 0437–4715 are very large. However, in the absence of specific model calculations, 0.9-3.7 Gyr appears to be the best estimate that presently is possible.

3.4. Comparison to other LMBP's

At the present time PSR J 0437–4715 is the only known example of a LMBP showing pulsed X-ray emission. X-rays have also been detected in the eclipsing millisecond pulsar PSR 1957+20 (Fruchter et al. 1992; Kulkarni et al. 1992). But the signal was far too weak to search for pulsations. The low X-ray detection rate LMBP's may be due to the fact that most of them lie not only at large distances but suffer concomitantly substantial interstellar absorption which is especially important in the soft X-ray range where PSR J 0437–4715 was detected (Becker et al. 1993). The X-ray spectrum of PSR1957+20 may be harder than that of PSR J 0437–4715.

A firmly established, important difference is that PSR 1957+20 is one of those systems where the nearby companion is being ablated by the pulsar wind (e.g., Fruchter et al. 1988). At present, it is not clear whether the X-ray flux originates from the pulsar itself or from the interaction of the pulsar wind with the companion that it evaporates (Fruchter et al. 1992). The origin of X-ray emission in a system such as PSR J 0437–4715 which consists of two very evolved and apparently non-interacting components constitutes a theoretical puzzle.

Finally, we note that the colours and the spectrum, although very noisy and rebinned to 5 nm, of star "S" which was considered but rejected by Kulkarni et al. (1991) as the optical counterpart of PSR 1855+09 are quite similar to those of the star observed by us. Kulkarni et al. find their distance estimate of star S irreconcilable with the upper limit on the parallax obtained from pulsar timing observations. Yet, even though red degenerate stars should be very numerous, it is curious that not only are PSR J 0437–4715 and PSR 1855+09 remarkably similar to one another according to their radio data but also both have a cool DC-type degenerate star within $\sim$1 arcsec of their radio positions.

4. Conclusions

The final identification of our star with the companion of PSR J 0437–4715 has to await parallax or further proper motion measurements. Detection of the 5.76-ms period also in the optical part of the spectrum would of course provide the most direct proof. However, the good agreement of the optical and the radio position and the optical proper motion measurement already provide a solid basis for the assumption that the companion is a cool degenerate star of spectral type DC13.

In PSR J 0437–4715 the age of the companion as constrained in Sect. 3.3 (0.9-3.7 Gyr) probably exceeds the currently reported spin-down age of the pulsar of 0.8 Gyr although a shorter cooling time cannot be ruled out. For a first clue whether the difference between these two ages is significant, a more precise determination of the absolute luminosity is important. But without specific model calculations no final conclusion can be drawn. To clarify this issue is essential because a very high cooling age would have important implications:

1. Since the pulsar cannot have formed after its less massive degenerate companion, the spin-down age of a pulsar would not always reflect its true age.
2. Pulsars can maintain a residual magnetic field of 10^8-10^9 G for several billion years.
3. With an increased life expectancy of LMBP's, the presently observed excess of the number of LMBP's over the number of LMXB's as noted by Kulkarni & Narayan (1988) would be reduced.

The first implication would be in contrast with the standard magnetic braking formula for pulsars (Manchester & Taylor 1977) even if a rather small braking index n is assumed. This formula attributes the spin down entirely to the torque of the magnetic dipole but does not in a quantitative way link the spin down rate to any basic properties of the pulsar. A higher age would, therefore, suggest that the spin down of some millisecond pulsars is affected by other factors, for instance a pulsar wind. Another consequence would be that magnetic field strengths inferred from an assumed proportionality to $(P\dot{P})^{1/2}$ present overestimates. One may perhaps speculate whether the presence of pulsed X-ray radiation and the possible mismatch between the spin-down age of the pulsar and the cooling age of the white dwarf companion are related.

That the life time of millisecond pulsars is not limited by magnetic field decay, the second conclusion, has been suggested by a number of authors (e.g., Kulkarni 1986; van den Heuvel et al. 1986; Srinivasan & Bhattacharya 1987) for different reasons. Callanan et al. 1989, deriving ages for the unidentified WD companion of PSR 1855+09 (therefore an upper limit to the luminosity was used) in a manner similar to that reported here, arrived at a similar conclusion. However, the case of PSR J 0437–4715 potentially provides the strongest direct evidence. Further work on theoretical models to explain the longevity of a basic magnetic field is, therefore, well justified. Some basic mechanisms are briefly discussed in van den Heuvel et al. (1986).

The possible need to considerably increase the lifetimes of millisecond pulsars in order to maintain the attractive identification of LMXB's as the progenitors of LMBP's had also been noticed previously (e.g., Srinivasan & Bhattacharya 1987; Kulkarni & Narayan 1988). Again, the observations of the companion of PSR J 0437–4715 represent one of the strongest incentives to consider this possibility more seriously.

Our discussion so far assumed that uncertainties of the age of the pulsar are negligible. However, it is not easy to separate the spin down of the pulsar from its own and the Earth's orbital motions. Accordingly, our observations might alternatively be taken as indicative that the true age of the pulsar ought to be higher. Provisional analysis of continued radio observations suggests, in fact, that the dynamical age of the pulsar may be as large 2 Gyrs (Manchester 1993, private communication). This is very close to our best estimate of the age of the companion so that there is no need to suspect a discrepancy that would call for a non-canonical interpretation.

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