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The rotation speed of the companion star in V395 Car (=2S0921–630)

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Abstract. We have obtained high resolution optical spectroscopy of the accretion disc corona source 2S0921–630 (=V395 Car) that constrains the spectral type of the companion star to be most probably K0III. At 6500 Å the secondary star is found to contribute $\sim$ 25% to the observed flux. The absorption line spectrum of the K0III companion star is broadened (compared to template stars) by a projected rotational velocity of 65±9 km s^{-1}(1-σ).

Key words: stars: neutron – stars: individual: V395 Car – stars: fundamental parameters – stars: binaries: general

1. Introduction

In spite of its low luminosity, 2S0921-630 has proved to be an interesting and important X-ray source. Discovered by SAS-3 and identified with a $\sim$15^m blue star, V395 Car (Li et al., 1978), subsequent studies (e.g. Branduardi-Raymont et al., 1983) showed that the spectrum was dominated by strong HeII λ4686 and Balmer emission, a characteristic of low-mass X-ray binaries (LMXBs). However, 2S0921-630 has an unusually low L_X/L_{opt} of $\sim$1 compared to most LMXBs, which was explained by the presence of partial optical and X-ray eclipses (Mason et al., 1987). This demonstrated that 2S0921-630 was a high inclination, *accretion-disc corona* (ADC) source. Only a handful of these are known (e.g. White et al., 1995) in which the compact object is permanently obscured from our view by the accretion disc, and hence the observed X-rays are scattered into our line-of-sight by a hot corona of gas above and below the disc. By implication, the intrinsic X-ray luminosity is much higher.

However, what is remarkable about 2S0921-630 is its long period. The other ADC sources are 2A1822-371, 4U2129+47 and 4U2127+19, which have relatively short orbital periods (5.6, 5.2 and 17.1 hrs respectively). Optical photometry and spectroscopy (Cowley et al., 1982 and Branduardi-Raymont et al., 1983) have indicated that V395 Car has a much longer orbital period of 9.02 days, with kinematic properties implying that it is located in the halo at a distance of $\sim$10 kpc (Cowley et al., 1982). The secondary star must then be evolved and intrinsically luminous in its own right, making the system very similar to the well-known halo giant Cyg X-2 (Casares et al., 1997; Orosz & Kuulkers, 1998). With its high inclination V395 Car is thus one of those rare LMXBs (along with Cyg X-2 and Her X-1) in which the secondary should be visible in spite of the presence of a luminous disc, and hence high resolution optical spectroscopy should reveal both the spectral type of the secondary and its rotation speed, thereby providing significant constraints on the system masses. Here we report the first results from such a study.

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⋆ Based on observations made at the European Southern Observatory, La Silla, Chile

Table 1. Log of observations

Date	UT	Exp. time
28/05/1998	23:41:48	1200s
29/05/1998	00:10:52	1200s
29/05/1998	00:32:55	1200s

2. Observations and data reduction

High resolution optical spectra of V395 Car were obtained on 1998 May 28/29 with the 3.5-m New Technology Telescope (NTT) at the European Southern Observatory (ESO) in Chile using the ESO Multi Mode Instrument (EMMI). We used the red arm with an order-separating OG 530 filter and grating #6 which gave a dispersion of 0.31 Å per pixel. The TEK 2048×2048 CCD was used, binned by a factor two in the spatial direction in order to reduce the readout noise. The dispersion direction was not binned. Very good seeing allowed us to use a slit width of 0.″8 which resulted in a spectral resolution of 0.83 Å. We took 3×1200 sec exposures of V395 Car (see Table 1) and Cu-Ar arc spectra were taken for wavelength calibration. In addition we observed template field stars with a variety of spectral types, whose rotational velocities are much less than the resolution of our data.

The data reduction and analysis was performed using the Starlink FIGARO package, the PAMELA routines of K. Horne and the MOLLY package of T. R. Marsh. Removal of the indi-

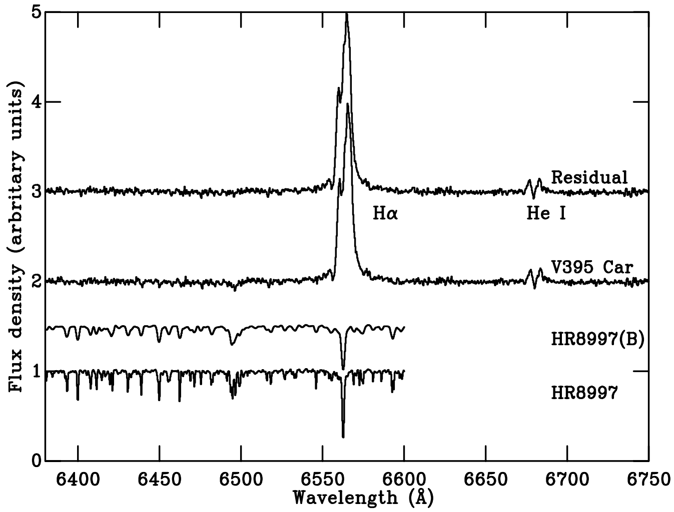

Fig. 1. The results of the optimal subtraction. From bottom to top: the template K0III star (HR8997), the template star broadened by 64 km s^{-1}, the variance-weighted average spectrum of V395 Car and the residual spectrum of V395 Car after subtracting the template star times f=0.25.The spectra have been normalized and shifted vertically for clarity.

vidual bias signal was achieved through subtraction of the mean overscan level on each frame. Small scale pixel-to-pixel sensitivity variations were removed with a flat-field frame prepared from observations of a tungsten lamp. One-dimensional spectra were extracted using the optimal-extraction algorithm of Horne (1986), and calibration of the wavelength scale was achieved using 5th order polynomial fits which gave an rms scatter of 0.02 Å. The stability of the final calibration was verified with the OH sky line at 6562.8 Å whose position was stable to within 0.1 Å.

3. The V395 Car spectrum

In Fig. 1 we show the variance-weighted average of our V395 Car spectra, which has a signal-to-noise ratio of about 40 in the continuum. The most noticeable features are the double peaked Hα and HeI 6678 Å emission lines. The double peaked nature of the emission lines is characteristic of a high inclination X-ray binary (Horne & Marsh 1986). This is consistent with the observed partial eclipse in the optical and X-rays (Mason et al., 1987).

4. The spectral type and rotational broadening of the companion star

We determine the spectral type of the companion star by minimizing the residuals after subtracting different template star spectra from the Doppler-corrected average spectrum. This method is sensitive to the rotational broadening $v \sin i$ and the fractional contribution of the companion star to the total flux (f; 1-f is the "veiling factor"). The template stars we use are in the spectral range F2–K2 III and were obtained during this observing run but also from previous runs at La Palma and with comparable dispersion.

First we determined the velocity shift of the individual spectra of V395 Car with respect to each template star spectrum by the method of cross-correlation (Tonry & Davis 1979). The V395 Car spectra were then interpolated onto a logarithmic wavelength scale (pixel size 14.5 km s^{-1}) using a $\sin x/x$ interpolation scheme to minimize data smoothing (Stover et al. 1980). The spectra of V395 Car were then Doppler-averaged to the rest frame of the template star.

In order to determine the rotational broadening $v \sin i$ we follow the standard procedure described by Marsh et al., (1994). Basically we subtracted a constant representing the fraction of light from the template star, multiplied by a rotationally broadened version of that template star. We broadened the template star spectrum from 0 to 100 km s^{-1} in steps of 1 km s^{-1} using the Gray rotation profile (Gray 1992). We then performed an optimal subtraction (Marsh et al., 1994) between the broadened template and averaged V395 Car spectra. The optimal subtraction routine adjusts the constant to minimize the residual scatter between the spectra. The scatter is measured by carrying out the subtraction and then computing the χ^2 between this and a smoothed version of itself. The constant, f, represents the fraction of light arising from the template spectrum, i.e. the secondary star. The optimal values of $v \sin i$ and f are obtained by minimising χ^2. The above analysis was performed in the spectral ranges 6380–6520 Å which excludes Hα and HeI 6678 Å. This was the only region common to all the templates stars and V395 Car. A linear limb-darkening coefficient of 0.60 was used (Al-Naimiy 1978).

Using the template stars covering a range in spectral type (F2–K2III) we found $v \sin i$ to be in the range 58–71 km s^{-1}. The minimum χ^2 occured at spectral type K0 with a $v \sin i$ of 64$\pm$ 9 km s^{-1}(1-σ) and the companion star contributing about 25% to the observed flux at $\sim$ 6500 Å. Fig. 1 shows the results of the optimal subtraction. This analysis assumes that the limb-darkening coefficient appropriate for the radiation in the line is the same as for the continuum. However, in reality this is not the case; the absorption lines in early-type stars will have core limb-darkening coefficients much less than that appropriate for the continuum (Collins & Truax 1995). In order to determine the extreme limits for $v \sin i$ we also repeated the above analysis for the K0 template star using zero and full limb-darkening. We found that $v \sin i$ changes by 4 km s^{-1}.

In order to estimate the systematic effects in estimating the spectral type and rotational broadening in V395 Car, we performed the same analysis but now using a template star of known spectral type. We broadened the target spectrum by 60 km s^{-1}, added noise and veiled it by 70% to produce a spectrum of comparable quality to that of V395 Car. We then repeated the broadening and optimal subtraction procedure using the same templates stars as was used for the V395 Car analysis, thereby determining the best fit. We found that with our analysis we were able to retrieved the spectral type to within two subclasses and the enforced rotational broadening and veiling accurate to 7%.

5. Discussion

5.1. Nature of the secondary star

In the ADC sources the observed X-rays are scattered into our line-of-sight by a hot corona of gas above and below the disc. The intrinsic X-ray emission is permanently obscured from our view by the accretion disc and its extended rim. The observation of partial X-ray eclipses constrains the binary inclination i to lie in the range 75°–90° (Mason et al., 1987). Thus, given our observed projected rotational broadening of the secondary star (64 ± 9 km s^{-1}) and these limits to i we determine the rotation of the secondary star to lie in the range 55.0–75.6 km s^{-1}(1-σ limits).

Furthermore, as a "steady" X-ray source, the secondary star must fill its Roche-lobe, and so its rotational velocity is given by

$$v_{\rm rot} = 611 \left[\frac{M_1(1+q)}{P_{hr}}\right]^{1/3} \left(\frac{R_{\rm L2}}{a}\right) \ \ {\rm km\ s^{-1}} \qquad (1)$$

where P_{hr} is the orbital period in hrs, q is the binary mass ratio (=M_2/M_1), M_1 is the mass of the neutron star and $R_{\rm L2}/a$ is the Roche-lobe radius of the secondary and depends only on q (Eggleton 1983). For a given mass for the compact object, M_1, we can solve Eq. (1) for q and hence M_2, and then also determine $R_{\rm L2}$. Assuming that the compact object has the mass of a canonical neutron star, 1.4 $M_\odot$, we find q, M_2 and $R_{\rm L2}$ to lie in the ranges 1.0–2.2, 1.4–3.1 $M_\odot$and 9.7–13.4 $R_\odot$respectively.

In a long period X-ray binary, loss of angular momentum via nuclear expansion of the secondary star drives the mass transfer, provided $q \lesssim 1.2$. In this case, the mass and radius of the secondary star are constrained to lie in the range 1.4–1.7 $M_\odot$and 9.7–10.3 $R_\odot$respectively. Recent theoretical models of King et al. (1997) have concluded that long period persistent X-ray binaries that contain neutron stars must have companion masses $M_2 \gtrsim 0.75\,M_\odot$. Our limits for M_2 are consistent with this idea. The mean density (ρ) of the secondary star is fixed by the orbital period (Frank et al., 1992). For 2S0921–630 we find $\rho = 2.4 \times 10^{-3}$ g cm^{-3}, which implies a K0III spectral type for the secondary star (Gray 1992). Note that this is consistent with our observed estimate (see Sect. 4).

5.2. P-Cygni profiles?

There is evidence for an outflow in 2S0921–630 arising from an accretion disc wind. The blue spectra of Branduardi-Raymont et al., (1983) show the Balmer emission lines to have a P-Cygni type profiles, where the blue wing of the line profile is absorbed.

As the binary inclination of 2S0921–630 is high, one would expect the P-Cygni profiles to be stronger at phase 0.5 that at phase 0.0, simply because at phase 0.5 one sees more of the accretion disc (Note we have used the usual phase convention i.e. phase 0.0 is defined when the secondary star is in front of the compact object.) The Balmer lines in the spectra of Branduardi-Raymont et al., (1983) taken at phase 0.52 (i.e. phase 0.77 in their convention) do indeed show P-Cygni profiles, Using the orbital ephemeris determined by Mason et al. (1987), we find that the orbital phase of our NTT spectrum to be 0.03 ± 0.03. Our spectrum does not show any evidence for a P-Cygni type profile, which is what one would expect, in a high inclination binary system.

The spectra of Branduardi-Raymont et al., (1983) taken near orbital phase 0.52 show strong HeI 4471 Å in absorption. This is clear evidence for irradiation of the secondary star (c.f. 2A1822-371; Harlaftis et al., 1997) as late-type stars do not show HeI lines. This suggests that the inner face of the secondary star, facing the compact object has a mean temperature of $\sim$20,000 K i.e. a spectrum of an early B type star. Note that since our NTT spectrum was taken near phase 0.0 the effects of irradiation will be the least and will most resemble the "true" spectral type of the secondary (compared to spectra taken at other orbital phases, where the accretion disc light and the effects of irradiation will contribute more).

5.3. Comparison with other systems

We can compare 2S0921–630 with the ADC source 4U2127+119. Both systems show Balmer P-Cygni type profiles and HeI 4471 Å in absorption. The probable high binary mass ratio in 4U2127+119 leads to unstable mass transfer from the secondary star, resulting in a common envelope (Bailyn & Grindlay 1987). In 4U2127+119 the HeI absorption line is blue shifted with respect to the mean velocity of the systemm believed to arise in a stream of gas leaving the outer Lagrangian point (Bailyn et al., 1989). If the mass transfer in 2S0921–630 is unstable, then we would also expect the HeI lines to be blue-shifted and have low non-sinusoidal velocity variations.

It is interesting to note the similarities between 2S0921–630 and Cyg X–2. Both systems are long period binaries in the halo of the Galaxy, they are at high inclination angles with evolved secondaries and both contain neutron stars. [Cyg X-2 must contain a neutron star because of the observed typeI X-ray bursts. For 2S0921–630 we cannot unequivocally state that it contains a neutron as no bursts have been seen. However, this may be a result of the natural consenquence of ADC sources. It should also be noted that our upper limit to M_1 suggests that it is a neutron star.] Also 2S0921–630 has a binary mass ratio $q \sim 1$, which is a factor of 3 higher than that of Cyg X–2 (q=0.34; Casares et al., 1997), suggesting that if the neutron stars in both systems have similar masses, then the secondary star in 2S0921–630 is more massive. However, it should be noted that the secondary star in 2S0921–630 is much cooler (K0III; $L_2 \sim 50\,L_\odot$) and hence less luminous than the secondary star in Cyg X–2 (A9III; $L_2 \sim 200\,L_\odot$), contrary to what we might have expected given their inferred masses. This discrepency can be reconciled if we postulate that we are seeing 2S0921–630 and Cyg X–2 at very different phases in their evolution. In Cyg X–2 we are probably seeing the secondary star which is high up on the giant branch and has lost its outer evelvope due to mass transfer and/or irradiation, leaving just the hot inner core of what had been initially a more massive star. Whereas, in 2S0921–630 the secondary star is not as evolved and so is near the base of the giant branch. Only detailed stellar evolution calculations will resolve this.

6. Conclusion

Using high resolution optical spectra, we estimate the spectral type of the companion star in 2S0921–630 (=V395 Car) to be a K0III star. By optimally subtracting different broadened versions of the companion star spectrum from the average V395 Car spectrum we determine the rotational broadening of the companion star to be 64±9 $\mathrm{km\,s^{-1}}$(1-σ) contributing $\sim$ 25% to the observed flux at 6500 Å.

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