Optical observations of close binary systems with a compact component

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The optical counterpart of the Z source GX 349+2

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Abstract

We have identified the optical counterpart of the Z source GX 349+2 with an 18th magnitude star, whose spectrum shows strong Hα-emission. If this emission originates from rotating material in an accretion disk around the neutron star we derive a lower limit to the orbital period of 1.0× $\sin^3$i day. If the companion is a giant we derive for spectral type G5 and M2 upper limits to the orbital period of 11.2 and 19.5 days, respectively. The redenning towards the source is $A_V \sim 5$.

2.1 Introduction

The persistently bright low-mass X-ray binaries can be divided into two groups, called Z sources and atoll sources, on the basis of their X-ray spectral and X-ray timing behaviour (Hasinger and van der Klis 1989; hereafter HK). The Z sources, which are the more luminous ones ($\sim 10^{38}$ erg s^{-1}) show a fairly uniform behaviour in the X-ray, radio and optical/UV bands (HK; Penninx 1989). They show three 'spectral branches' in an 'X-ray colour-colour diagram' with correlated timing characteristics. Of the six known Z sources, five have been detected as weak and strongly variable radio sources (see also Cooke and Ponman 1991; hereafter CP). Only two Z sources have been identified optically so far, Cyg X-2 (Giaconni et al. 1967) and Sco X-1 (Giaconni et al. 1962). Of the Z sources that have not been optically identified three have very large interstellar extinction, as derived from X-ray observations (Schulz, Hasinger and Trümper 1989). The remaining source GX 349+2 (Sco X-2) has a relative low value of interstellar absorption (Schulz et al. 1989) and might therefore be relatively easily detectable at optical wavelengths. The X-ray characteristics of GX 349+2 strongly resemble those of Sco X-1 (see e.g. HK). One might therefore expect that the intrinsic properties of the optical counterpart of GX 349+2 would also resemble those of Sco X-1.

We obtained two spectra of the optical candidate of GX 349+2, which was suggested by CP on the basis of an accurate radio position, and looked for spectral characteristics that could support an optical identification of this Z source.

2.2 Observations and Analysis

We observed the optical candidate of GX349+2 (star 6 in the finding chart published by Jernigan et al. 1979), with EFOSC on the ESO 3.6m telescope on August 1, 1990. We made two spectra

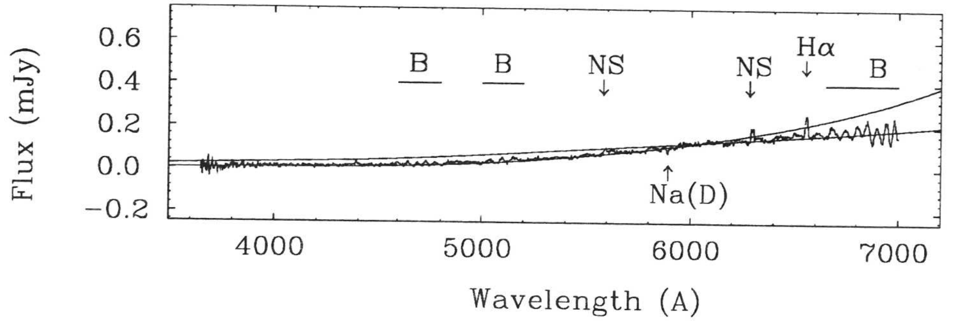

Figure 2.1. The 90 min spectrum of the proposed optical counterpart of GX 349+2. The following features have been indicated: the Hα emission and Na(D) absorption line; broad features due to the fringes in the CCD image (B) and two night-sky lines (NS). A comparison with a heavily absorbed flat spectrum is also given. The two lines correspond to deredenned fluxes of 1.5 and 40 mJy and A_V of 3 and 7, respectively

with the B300 grism (dispersion 230 Å mm^{-1}; 3.2 Å $pixel^{-1}$) and a high resolution RCA CCD camera covering the range ~3600–7000 Å . Both spectra were taken through a 1.5" slit giving a resolution of 13 Å (FWHM of the Helium–Argon lines of the comparison spectrum). The first spectrum was taken at UT Aug 1 1990 1:20 (45 min integration time), and the second was taken at UT Aug 1 1990 2:24 (90 min).

During the 45 min exposure, part of the spectrum fell on some bad columns of the CCD, which caused problems in the night-sky subtraction of the blue part of the spectrum. The sky was bright and strong night-sky lines are visible on the images. Fringes could not be fully taken out, and resulted in broad artificial features in the spectrum. The 90 min spectrum is shown in Fig. 2.1. The spectrum was wavelength calibrated using a Helium-Argon spectrum, and flux calibrated using an observation of Wolf 485 (Oke 1974). The subtraction of the background spectra, in which fringes are somewhat shifted in wavelength with respect to the star spectrum, resulted in the broad features in Fig. 2.1. The background subtraction was not perfect, and resulted in two features of the night-sky lines. We detect Hα emission at 6556.2 ± 0.6 Å, and Na(D) interstellar absorption at 5890.6 ± 0.6 Å. The Hα emission is also detected in the 45 min spectrum. The equivalent widths of both Hα lines are 7.0 ± 0.3 Å; the full width at half maximum is ~ 13.2 Å. The central wavelength of the Hα line in the 45 min spectrum is shifted with respect to the same line in the 90 min spectum by +0.6±0.4 Å. The equivalent width of the Na(D) line is 3.7 ± 0.4 Å. The quoted errors are 1σ-errors.

Other stars that were visible on the CCD, show no Hα in emission; some show Hα in absorption.

Additionally we made B and V band images of the optical counterpart of GX 349+2. We used star E7-u as a calibration star (Graham 1982). The magnitudes derived for the optical counterpart of GX 349+2, are B = 20.0±0.1 and V = 18.4±0.1. CP derived B = 20.2 and V = 18.7. They used stars A and B (Penston et al. 1975) as comparison stars. We derive for star B in our B band image a brightness of 15.28, consistent with that given by Penston (m_B = 15.35).

2.3 Discussion

In view of the known properties of the optical counterparts of low-mass X-ray binaries, the presence of Hα emission in the spectrum of star 6 is evidence that this object is the optical counterpart of the X-ray source. The radial velocity, as derived from the central wavelength of the Hα-line (−310±30 km/s) would not be expected from a single star being a member of the disk population, and supports this identification.

The strength of the Hα line (EW ~ 7.0 Å) is on the high side when compared to the Z sources Cyg X-2 (EW ~ 3.3–6.9 Å, van Paradijs et al. 1990) and Sco X-1 (Willis et al. 1980). If other spectral features as found in Sco X-1 and Cyg X-2 (He II lines, Hβ, Hγ, Hδ, λ4640) were present in GX 349+2 with similar strengths, we would not have detected them. In contrast to the Z sources, the atoll sources show no such Hα emission lines (Canizares, McClintock and Grindlay 1979). Hα absorption lines are possibly observed in the atoll sources 1636-53 and 1735-44 by Canizares et al. (1979). It is not yet possible to decide whether the difference in presence of Hα emission lines between the atoll sources and Z sources imply fundamental differences in their structure or merely differences of degree in one or another fundamental parameter of the system (e.g. size of the disk).

The intrinsic optical spectra of disks are in general fairly flat (see e.g. van Paradijs 1983; Neugebauer 1969 for Sco X-1). We have added in Fig. 2.1 flat spectra that are strongly absorbed. The derived spectrum is consistent with being a heavily absorbed flat spectrum (given the limited quality of the spectrum), in which case the spectrum is absorbed by A_V ~ 4-6, and a dereddened flux is ~ 5-20 mJy. This is similar to what was found by CP, who derived A_V~ 5, and a dereddened m_V=13.7 (13 mJy).

The wavelength difference (2.3±0.6 Å) between the observed Na(D) line and rest wavelength (assuming both Na(D) lines have equal strenghts) gives an average radial velocity of −120±30 km/s for the absorbing medium. This velocity is probably the result of galactic rotation of the absorbing medium. The strength of the Na(D) line (equivalenth width of 3.7 Å) is consistent with the derived interstellar absorption (A_V~ 5, CP, see also Fig. 2.1).

The FWHM of the Hα line (~ 13 Å) is dominated by instrumental broadening. If we assume that this emission originates from an accretion disk this gives an upper limit for the velocity of rotating material of 300 km/s. Observed velocities of the rotating material are up to ~ 1000 (possibly 10 000 km/s) in other low-mass X-ray binaries (Canizares et al. 1979). The upper limit to the rotating velocity is determined by the Kepler's third law, and gives a lower limit to the distance to the neutron star of the region from which the Hα emission region originates of ~ 2.1 $10^6\times$ $\sin^2$i km (assuming a neutron star mass of 1.4 $M_\odot$; i is the inclination). If we take this distance as lower limit to the radius of the Roche-lobe of the neutron star, and assume a lower mass limit of 0.08 $M_\odot$ for the companion star, we derive a lower limit to the orbital period of ~ 1.0$\times$ $\sin^3$i day. However, if the Hα emission originates from a (X-ray heated) region on the companion star, or another fixed region in the binary frame (like the hot spot on the outside of the disk), than the derived lower limits are not valid.

Orbital velocity measurements of optical emission lines of Z sources have led to semi-amplitudes K ~ 60 km/s for Sco X-1 (P = 18.9h; Cowley and Crampton 1975), and K ~ 200 km/s (Hβ) for Cyg X-2 (P = 9.8d; Cowley, Crampton and Hutchings 1979). For the atoll sources 4U1636-53, 4U1735-44 and GX 9+9 (all of which have orbital periods near 4 hr) semi-amplitudes K ~ 200 km/s have been found (Cowley, Hutchings and Crampton 1988). Assuming that GX 349+2 has a velocity amplitude of 200 km/s, one would expect that the binary systematic velocity is between −100 – −500 km/s. Sco X-1 and Cyg X-2 do not rotate with galactic rotation, and the indicated systematic velocity is no surprise.

The observed differences between the atoll and Z sources have been interpreted in terms of a difference in ***neutron-star magnetic field strength***, ~ 10^{10} Gauss for Z sources, and $\lesssim 10^{8.5}$ Gauss for atoll sources (HK). HK have suggested that these differences may have an evolutionary connection, as the Z and atoll sources also seem to differ with respect to the stellar type of the mass donor star (both known companions of Z sources are [sub-]giants, whereas 4 (out of 10) known companions of atoll sources have [main-sequence or degenerate] dwarfs as mass donors).

The suggestion of HK can be tested by determining the character of the mass donor of GX 349+2. The best way to check this would be to determine the orbital period using velocity measurement of the Hα-line.

If the companion were a giant (as in the case of Cyg X-2), one might be able to detect spectral absorption features of the giant companion. We did not find any absorption features in our spectra. However, this non-detection is not very stringent; absorption features as observed in the spectrum of Cyg X-2 (see e.g. van Paradijs et al. 1990, e.g. Hβ with equivalenth width of $\sim$ 2.5–7.5 Å), would not be detectable in the present spectrum of star 6.

If the companion were a large giant, we would also expect that it would be a major contributor of the IR-light. The dereddened H-band flux of CP $m_{\rm H}$=14.2 (possible completely due to reprocessed X rays) can be used as an upper limit to the IR light from a mass donor. We will use an upper limit of $m_{\rm J}\gtrsim 14.2$ (J is more commonly used than H as a reference band) to derive an upper limit for the luminosity and orbital period from a possible giant companion. Using $m_{\rm V}= m_{\rm J}$ + (V–J), with V–J as given as a function of spectral type by Johnson (1966), we obtain $m_{\rm V}\gtrsim 15.72$ and $m_{\rm V}\gtrsim 17.28$ for assumed spectral types of the companion star of G5 and M2 respectively. Using a distance of 9.2 kpc (Penninx 1989), this gives absolute visual magnitudes $M_{\rm V}\gtrsim 0.90$ (G5) and $M_{\rm V}\gtrsim 2.46$ (M2). Using the relation between absolute magnitude, stellar radius and (stellar-type dependent) surface bightness, given by Popper (1980), we find corresponding upper limits to the companion star of GX 349+2 of 9.7 $R_{\odot}$ and 13.7 $R_{\odot}$, for assumed spectral types of G5 and M2, respectively. Finally, using the relation between orbital period and average density of the companion star (and assuming q=$M_{\rm opt}/M_{\rm ns}\lesssim 0.8$, see Paczynski 1971), we find corresponding upper limits to the orbital period of GX 349+2 of 11.2 and 19.5 days, respectively.

Vrtilek et al. (1990, 1991) showed that for the Z sources Cyg X-2 and Sco X-1 the intensity of the reprocessed X rays (optical/UV radiation) varies by a factor of three between flaring, normal and horizontal branch. Since GX 349+2 has never been observed in the horizontal branch, we expect that a brightness variation of the optical counterpart (which is correlated with the X-ray variability) is less than in the case of Cyg X-2 and Sco X-1, probably $\sim 50-100$ %; this assumes that a possible mass donor contibutes insignificantly.

A project to find colour changes as a result of changing ratios of the brightnesses of a blue disk and a possible red giant, and a study to derive an orbital velocity curve are under way.

2.4 Conclusion

Our observations of star 6 in the finding chart of Jernigan et al. (1979) support the proposal of CP that this star is the optical counterpart of GX 349+2. The source shows strong Hα in emission, typical for Z sources.

Acknowledgements

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