K-band spectroscopy of the intermediate polar XY Ari

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ABSTRACT
We present the K-band infrared spectrum of the intermediate polar XY Ari. The spectrum confirms the cataclysmic binary nature of XY Ari, showing emission lines of He I (λ2.0587 μm) and the Brackett and Paschen series of H I. The broad nature of these lines suggest an origin in an accretion disc. The spectrum is strongly reddened by absorption within the molecular cloud Lynds 1457 and shows prominent absorption features from the secondary star, from which we determine a spectral type for the secondary of M0V. The secondary contributes 80 ± 6% of the K-band light. We derive a visual extinction to XY Ari of $A_v = 11.5 ± 0.3$ and a distance of $d = 270 ± 100$ pc, placing XY Ari behind the molecular cloud.

Key words: binaries: close – stars: individual: XY Ari – intermediate polars, accretion, cataclysmic variables – infrared: stars

1 INTRODUCTION

XY Ari (formerly known as H0253+193) was discovered as an X-ray source using the Einstein satellite (7). It lies within 5′ of the core of the molecular cloud Lynds 1457 and was initially suggested to be an X-ray emitting protostar. However, the discovery of X-ray pulsations with a 206-s period (7) suggested that the X-rays originated from accretion onto a strongly magnetised, rotating compact object. 7 noted that the X-ray properties of XY Ari strongly resemble those of an intermediate polar (IP) and the binary nature of the system was confirmed with the discovery of X-ray eclipses recurring with a 6.06-h orbital period (7). XY Ari is the only intermediate polar to exhibit deep X-ray eclipses.

High extinction through the molecular cloud means that XY Ari is not observable at optical wavelengths. The infrared (IR) counterpart was identified by 7. Infrared photometry was undertaken by 7 who modelled the ellipsoidal variations and found a mass ratio in the range 0.43 < q < 0.71 and an inclination in the range 80° < i < 87°. Here we present the IR (K-band) spectrum of XY Ari. We use the spectrum to determine the spectral type and contribution of the secondary star, as well as the distance and extinction to XY Ari.

2 OBSERVATIONS

The spectrum of XY Ari presented in this paper was obtained on the night of 1995 October 20 with the Cooled Grating Spectrometer 4 (CGS4) on the 3.8 m United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, Hawaii. CGS4 is a 1–5 micron spectrometer containing an InSb array with 256×256 pixels. The 75 l mm$^{-1}$ grating in the first order with the 150 mm camera gave a resolution of approximately 350 km s$^{-1}$ and a wavelength range of approximately 0.7μm.

Optimum spectral sampling and bad pixel removal were obtained by mechanically shifting the array over two pixels in the dispersion direction in steps of 0.5 pixels. We employed the non-destructive readout mode of the detector to reduce the readout noise. In order to compensate for fluctuating atmospheric OH$^-$ emission lines we took relatively short exposures (typically 30 seconds) and nodded the telescope primary so that the object spectrum switched between two different spatial positions on the detector. The slit width was 1.2 arcseconds (projecting to approximately 1 pixel on the detector) and was oriented at the parallactic angle. The seeing disc was equal to or slightly larger than the slit width throughout. The observations were made in photometric conditions.

A full journal of observations is presented in table 1.
Table 1. Journal of observations. The spectral types of the dwarf stars have been taken from the catalogue of ? unless otherwise noted.

<table>
<thead>
<tr>
<th>Object</th>
<th>Spectral Type</th>
<th>Date</th>
<th>UTC start</th>
<th>UTC end</th>
<th>Exposure time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XY Ari</td>
<td>K5V</td>
<td>20/10/95</td>
<td>09:07</td>
<td>12:22</td>
<td>5700</td>
</tr>
<tr>
<td>GL 775</td>
<td>K5V</td>
<td>20/10/95</td>
<td>06:20</td>
<td>06:27</td>
<td>96</td>
</tr>
<tr>
<td>GL 764.1b</td>
<td>K7V</td>
<td>20/10/95</td>
<td>05:43</td>
<td>05:52</td>
<td>240</td>
</tr>
<tr>
<td>GL 154</td>
<td>M0V</td>
<td>21/10/95</td>
<td>09:39</td>
<td>09:48</td>
<td>192</td>
</tr>
<tr>
<td>GL 229</td>
<td>M1V</td>
<td>06/02/96</td>
<td>05:00</td>
<td>05:08</td>
<td>72</td>
</tr>
</tbody>
</table>

*a?

3 DATA REDUCTION

The initial steps in the reduction of the 2D frames were performed automatically by the CGS4 data reduction system (?). These were: the application of the bad pixel mask, bias and dark frame subtraction, flat field division, interlacing integrations taken at different detector positions, and co-adding and subtracting nodded frames. Further details of the above procedures may be found in the review by ?.

In order to obtain 1D data, we removed the residual sky by subtracting a polynomial fit and then extracted the spectra using an optimal extraction technique (?). The next step was the removal of the ripple arising from variations in the star brightness between integrations (i.e. at different detector positions). These variations were due to changes in the seeing, sky transparency and the slight motion of the stellar image relative to the slit.

There were two stages to the calibration of the spectra. The first was the calibration of the wavelength scale using krypton arc-lamp exposures. We had no readable arc frames from the night of 1995 October 20, so an arc frame from the next night was used. A second-order polynomial fit to the arc lines yielded an error of less than 0.001 microns (rms) and the error in the fit showed no systematic trend with wavelength. The final step in the spectral calibration was the removal of telluric features and flux calibration. This was performed by dividing the spectra to be calibrated by the spectrum of an F-type standard star, with its prominent stellar features interpolated across. We then multiplied the result by the known flux of the standard at each wavelength, determined using a black body function set to the same effective temperature and flux as the standard. As well as correcting for the spectral response of the detector, this procedure also removed telluric absorption features from the object spectra.

4 RESULTS

Figure 1 shows the K-band spectra of the IP XY Ari and the M0-dwarf Gl 154. The spectrum of XY Ari shows strong, broad emission lines of He I (λ20587 µm) and the Brackett and Paschen series of H1, confirming the cataclysmic variable nature of this system. The large velocity widths of these lines imply an accretion disc origin, consistent with the study of ?, who found evidence for IR-emitting gas around the white dwarf from the H-band lightcurve. The spectrum also shows strong absorption features of Na I, Ca I and 12CO due to the secondary star. Note that the atomic features in reality consist of a blend from many atomic species (?) and the identification given here is that of the strongest contributor.

4.1 Secondary star spectral type

In order to determine the spectral type of the secondary star in XY Ari, and to determine its contribution to the K-band flux, we used an optimal subtraction technique (e.g. ?). Before this could be carried out however, we needed to account for reddening by the molecular cloud, as this could affect the apparent spectral type of the secondary star by altering the relative strengths of the secondary star absorption features. To account for this we de-reddened the spectra of XY Ari using the “standard” extinction curve of ? and colour excesses of 2 < E(B − V) < 5. The optimal subtraction technique described below was applied to the dereddened spectrum in order to find the spectral type of the secondary and its contribution to the K-band flux. It was found that, within the range of colour excess used, the dereddening did not have a significant effect on the results obtained. Therefore, in order to determine the spectral type a colour excess of E(B − V) = 4 was used. This value of the colour excess produced a dereddened spectrum whose continuum slope closely matched that of the late-K and early-M dwarfs.

The optimal subtraction technique works as follows; first we normalised the spectra of XY Ari and the spectral type template stars by dividing by a first-order polynomial fit to the continuum. A constant times the normalised template spectrum was then subtracted from the normalised spectrum of XY Ari and the constant adjusted so as to minimise the residual scatter in regions containing secondary star features. The scatter was calculated by carrying out the subtraction and then computing the χ² statistic between the residual spectrum and a smoothed version of this residual. Prior to the subtraction, the template spectra should ideally be broadened to account for the rotational velocity of the secondary star; the low velocity resolution of our data made this step unnecessary. The value obtained for the percentage contribution naturally depends on spectral type, the correct spectral type being the one which minimises the value of χ². The error in the percentage contribution is the formal error calculated from the variation in χ².

For our data, however, the value of χ² was not a revealing statistic, as several spectral type templates produced reduced-χ² values of less than one. In order to select the best-fitting spectral type the results of the optimal extraction technique were examined by-eye. In order to do this, we added a flat continuum to the spectral-type template spectrum, so that the template contributed the same amount to the K-band flux as was suggested by the optimal subtraction technique. The resulting spectra are shown in figure 2, over-plotted on the spectrum of XY Ari. From this figure, we can see that the continuum slope around 2.1 µm is well fitted by the K7V and M0V stars, but poorly fitted by the
K-band Spectroscopy of XY Ari

Figure 1. K-band spectra of the IP XY Ari, and the M-dwarf Gl154. The spectra have been normalized by dividing by the flux at 2.24 µm and then offset by adding a multiple of 0.4 to each spectrum. Also shown is the spectrum of an F0V star, normalized by dividing by a spline fit to the continuum, which indicates the location of telluric features.

4.2 The extinction

If we denote the intrinsic apparent magnitude (i.e. the apparent magnitude we would observe if there were no extinction) as \( m_λ^i \), and the absolute magnitude as \( M_λ \), then

\[
m_λ^i - M_λ = 5 \log_{10} \left( \frac{d}{10} \right)
\]

where \( d \) is the distance in pc. If the observed apparent magnitude is \( m_λ \), then

\[
m_λ = m_λ^i + A_λ
\]

where \( A_λ \) is the extinction at wavelength \( λ \). Equations (1) & (2) imply

\[
m_K^i - m_J^i = (A_K - A_J) + (M_K - M_J)
\]

which, using the extinction curve of ? can be re-written

\[
m_K^i - m_J^i = (M_K - M_J) - 0.5E_{(B-V)}
\]

We can apply this to the secondary star in XY Ari in order to determine the extinction. For a secondary of type early-M, the secondary star in a CV contributes roughly the same percentage of the J- and K-band light (see, for example, figure 5 in ?). We therefore assume that the secondary contributes 80% of the J- and K-band flux in XY Ari. Combined with the J- and K-band magnitudes for XY Ari from ? of \( J = 16.0 \) and \( K = 13.3 \) this gives \( m_K^i = 13.6 \) and \( m_J^i = 16.3 \) for the observed apparent magnitudes of the secondary star in XY Ari. From ? the absolute K- and J-band magnitudes for a M0V star are \( M_K = 5.22 \) and \( M_J = 6.06 \). Assuming the error in the extinction is dominated by the error in estimating the spectral type of the secondary star in XY Ari, this gives a colour excess of \( E_{(B-V)} = 3.7 \pm 0.1 \) or a visual extinction of \( A_V = 11.5 \pm 0.3 \).

4.3 The distance to XY Ari

The distances to CVs can be measured from K-band spectra using a modification of a method first proposed by ?. The distance modulus can be written in terms of the K-band surface brightness of the secondary star, \( S_K \), as

\[
S_K = m_K^i - A_K + 5 - 5 \log d + 5 \log(R/R_⊙)
\]

where \( A_K \) is the K-band extinction and \( R \) is the radius of the secondary star. \( m_K^i \) was determined in section 4.2. Using the extinction derived in section 4.2 and the extinction curve of ? we estimate \( A_K = 1.3 \pm 0.1 \). Assuming the error in \( V - K \) to be dominated by the error in estimating the spectral type of the secondary star in XY Ari, ? gives a
Figure 2. Fits to the K-band spectra of the IP XY Ari. Template spectra with a flat continuum added according to the results of the optimal subtraction are shown in bold, over-plotted on the spectrum of XY Ari, plotted with a dashed line.

$V - K$ colour of $V - K = 3.7 \pm 0.4$. Using the calibrations of this gives $S_k = 4.4 \pm 0.1$. We have estimated the radius of the secondary star to be $R/R_\odot = 0.7 \pm 0.2$ from the orbital period-radius relation (equation 11) given by ?. These values, in conjunction with equation 5 gives a distance to XY Ari of $270 \pm 100$ pc. This places XY Ari well behind the molecular cloud, for which ? derived a distance of $d < 110$ pc.

By assuming the light from XY Ari consisted entirely of light from a secondary star of spectral type K8, ? found their $J$- and $K$-band colours were consistent with a distance of 200 pc and a visual extinction of $A_V = 11.5$ mag. Our values are in agreement with these results.

5 CONCLUSIONS

The K-band spectrum of XY Ari shows strong, broad emission lines, confirming the cataclysmic variable nature of the object. The spectrum is strongly reddened and shows prominent absorption features from the secondary star. We estimate the spectral type of the secondary star to be M0V. The secondary star contributes $80 \pm 6\%$ of the K-band flux. Comparing the observed infrared colours with the intrinsic colour of the secondary star we estimate a distance to XY Ari of $270 \pm 100$ pc and a visual extinction of $A_V = 11.5 \pm 0.3$, placing XY Ari behind the molecular cloud Lynds 1457.

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