The orbital period of intermediate polar 1WGA J1958.2+3232

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Abstract. The detection of the orbital period of 4h36 is reported for the new Intermediate Polar 1WGA J1958.2+3232. The orbital period was derived from time-resolved photometric and spectral observations. We also confirmed the 733 s spin period of the White Dwarf consistent with the X-ray pulsations and were able to distinguish the beat period in the light curve. Strong modulations with orbital period are detected in the emission lines from spectral observations. They show the presence of a bright hot spot on the edge of the accretion disk. The parameters of this recently discovered Intermediate Polar are determined.

Key words. stars: individual: 1 WGA J1958.2+3232 – stars: novae, cataclysmic variables – stars: binaries: close – X-rays

1. Introduction

Cataclysmic variables (CVs) are close binary systems in which mass is transferred from a red dwarf star that fills its Roche lobe onto a white dwarf (WD). Intermediate polars (or DQ Her systems) are a subclass of magnetic cataclysmic variables with an asynchronously rotating ($P_{\text{spin}} < P_{\text{orb}}$) magnetic white dwarf (Patterson 1994; Warner 1995). The accretion flow from the red dwarf star forms an accretion disk around the white dwarf, and this disk is disrupted by the magnetic field close to the white dwarf. Within the magnetospheric radius, the material is channelled towards the magnetic polar regions of the white dwarf (Rosen et al. 1988).

The recently discovered pulsating X-ray source 1WGA J1958.2+3232 (Israel et al. 1998) was announced as a new Intermediate Polar (IP) by Negueruela et al. (2000) from spectral observations. Strong modulations of this source in X-rays were obtained from ROSAT PSPC (721 ± 14 s) and a more accurate value 734 ± 1 s from ASCA are presented by Israel et al. (1998) and Israel et al. (1999). Photometric observations of the optical counterpart of 1WGA J1958.2+3232 exhibited strong optical variations, compatible with the X-ray (~12 min) period (Uslenghi et al. 2000). This modulation was interpreted as evidence of a spin period of the WD in this close binary system.

In this paper we present the results of new photometric and spectral observations of this system.

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Table 1. Observations log

<table>
<thead>
<tr>
<th>HJD start</th>
<th>Duration</th>
<th>Time of exposure</th>
<th>Band</th>
<th>Telescope</th>
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<td></td>
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<td></td>
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<td>120</td>
<td>$R_c$</td>
<td>1.5 m</td>
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<td>435</td>
<td>120</td>
<td>$R_c$</td>
<td>1.5 m</td>
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<td>461</td>
<td>700</td>
<td>4025–5600 Å</td>
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<tr>
<td>763.678</td>
<td>319</td>
<td>700/350</td>
<td>4025–5600 Å</td>
<td>2.12 m</td>
</tr>
</tbody>
</table>

a 2 August.

2. Observations

The CCD photometric and spectral observations of the 1WGA J1958.2+3232 were carried out on 2–5 August 2000 at the 1.5 m and 2.12 m telescopes of the Observatorio Astronomico Nacional, San Pedro Martir of the Institute of Astronomy of UNAM, Mexico. The observations log is presented in Table 1.

2.1. Optical photometry

We obtained $R_c$-band time-resolved photometry of the optical counterpart of 1WGA J1958.2+3232 during two nights in August 2000 at the 1.5 m telescope. The telescope was equipped with a 1024 × 1024 pixel SITE CCD. The frame was reduced in size to 450 × 450 pix for faster read-out. It accommodated the object and at least two comparison stars in the field of view. The exposure times were 120 s, which leads to a time resolution of 169 s, taking into account dead time between readouts. In total the object was monitored during ~13.55 h (6.3 h the first night and 7.25 h the second). The data reduction was
The orbital period of 1WGA J1958.2+3232 was obtained from the dispersion of magnitudes in the differential photometry of comparison stars with similar brightness. The dispersion ranged from 0.005 to 0.01 mag. We did not obtain an absolute calibration for our photometric data.

2.2. Optical spectroscopy

Time-resolved spectroscopy of the optical counterpart of 1WGA J1958.2+3232 was obtained on 4–6 Aug., 2000 using the Boller & Chivens spectrograph installed in the Cassegrain focus of the 2.12 m telescope. We used the 400 l/mm grating with a 13.54 blaze in the second order, combined with the blue BG39 filter and CCD TEK1024 × 1024 pix with a 0.24 μm pixel size. The slit width was 1.5 arcsec projected on the sky. This combination yielded a spectral resolution of 2.7 Å FWHM and provided a wavelength coverage of 4050–5600 Å. Of three nights of spectral observations, the second and third nights were disrupted by passing clouds. However the seeing was satisfactory with images <1.2 arcsec. The slit was oriented with position angle of 306° to accommodate a nearby star for the flux level control. The exposure time in the first two nights was 700 s, while on the third night, 700 and 350 s. The He-Ar comparison spectra were taken every ~120 min. A total of 68 spectra was obtained. The IRAF long slit spectroscopic reduction package was used for extraction of spectra, wavelength and flux calibrations.

3. Results

3.1. Light curve. Orbital and spin modulations

The object shows multi-scale time variability with a range of 0.3 magnitudes (see Fig. 1). Four pronounced eclipse-like depressions obviously shape the light curve. Strong flickering with optical pulse amplitude (semi-amplitude) of about 0.1 magnitude is also obvious in the light curve detected and identified earlier (Israel et al. 1998; Uslenghi et al. 2000) as spin related modulations. The photometric data of 1WGA J1958.2+3232 were analyzed for periodicities using the Discrete Fourier Transform (DFT) code (Deeming 1975) with a CLEAN procedure (Roberts et al. 1987). The CLEANed power spectrum (Fig. 2) of $R_c$ photometric data shows a clear peak at $\Omega_{\text{orb}} = 5.54996 \pm 0.39624$ (1/day), corresponding to $P_{\text{orb}} = 0.1802 \pm 0.0065d$. This peak is caused by the above mentioned eclipses in the light curve and clearly marks the orbital period of the system.

We also found a significant peak at the spin period $\omega_{\text{rot}}$ of the WD corresponding to $733.82 \pm 1.25$ s. This period is in excellent agreement with that recently discovered by ASCA X-ray pulsations (Israel et al. 1999). The beat frequencies at $\omega_{\text{rot}} - \Omega_{\text{orb}}$, $\omega_{\text{rot}} + \Omega_{\text{orb}}$, are also present in the CLEANed power spectrum but with a smaller number of iterations (see insert in the upper right corner of the Fig. 2). The harmonics of the basic frequencies $\Omega_{\text{orb}}$ and $\omega_{\text{rot}}$ are detected as well. Besides these, there are

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1 ESO-MIDAS is a copyright protected software product of the European Southern Observatory, and provides general tools for image processing and data reduction.

2 IRAF is the Image Reduction and Analysis Facility, a general purpose software system for the reduction and analysis of astronomical data. IRAF is written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation.
3.2. Radial velocity variations and binary system parameters

The spectrum of 1WGA J1958.2+3232 shows features characteristic for Cataclysmic Variables. We refer to Negueruela et al. (2000), who obtained a spectrum of the object in a wider spectral range and with better spectral resolution. We also obtained time-resolved spectroscopy of 1WGA J1958.2+3232 around the emission lines of Hβ and HeII, covering several orbits. Thus, we were able to examine periodical variations in the spectrum of the object, primarily in the emission lines. The simple stacking of consecutive spectra onto the trailed spectrum showed strong variability in the lines. It is distinct in the Balmer lines and in the higher excitation lines of ionized Helium. The Balmer lines are double-peak with an S-wave moving inside, which makes it hard to see the periodic pattern. In the HeII 4686 line the central narrow component dominates in most of the phases, and it shows clear sinusoidal variation.

In order to determine the orbital elements we measured the radial velocities (RV) of Hβ applying the double Gaussian deconvolution method introduced by Schneider & Young (1980), and further developed by Shafter (1983). This method is especially efficient for measurements of the orbital motion of CVs with a prominent spot at the edge of the accretion disk, contaminating the central parts of the emission lines. It allows us to measure RV variations using the wings of the lines. The width of the Gaussians were chosen to be slightly larger than our spectral resolution (8.5 Å), where deconvolution was reached at all orbital phases. The radial velocities were measured as a function of distance $a$ between the Gaussians, and then the diagnostic diagrams were constructed using an initial guess for the orbital period, derived from photometry and from preliminary radial velocity measurements via Gaussian fits to the lines. The optimal value of separation ($a = 1175 \text{ km s}^{-1}$) was determined from the diagnostic diagrams, and the RV values measured for these Gaussian separations were again subjected to a power spectrum analysis in order to refine the period. The spectroscopic period peaked at a slightly longer value, than the photometric period (however within the errors of the photometric period). This method quickly converged and after
two iterations no further improvement was achieved. The diagnostic diagrams for H\textsubscript{\beta} are shown in Fig. 3. Figure 4 (top) shows the H\textsubscript{\beta} radial velocity curve.

A narrow single Gaussian profile was fitted to the prominent emission features in the profile of He\textsubscript{ii} \lambda4686 Å, and the measured line centers were used to determine the radial velocity solution for 1 WGA J1958.2+3232. The radial velocity curve for He\textsubscript{ii} \lambda4686 line is presented in the middle panel of Fig. 4. These measurements were also subjected to the power spectrum analysis. The obtained orbital period is in good agreement with the values derived from the photometry and the H\textsubscript{\beta} line radial velocities. The power spectra around the values corresponding to the orbital period from these three independent determinations are plotted in Fig. 5. One can see the excellent match of the central peak. We adopted 0\degree 18152 ± 0\degree 00011 as the final value for the orbital period of 1 WGA J1958.2+3232 from our observations. Longer time base observations are needed to improve this value.

Each of the radial velocity curves was fitted using a least-squares routine of the form

\[ v(t) = \gamma_0 + K_1 \sin(2\pi(t - t_0)/P), \]

where \( \gamma_0 \) is the systematic velocity of the system, and \( K_1 \) is the semi-amplitude of radial velocity, both in \( \text{km s}^{-1} \). The observation time is \( t \), the epoch \( t_0 = 2451761.2281 \pm 0\degree 0001 \) corresponds to the \( \pm \) zero crossing of the H\textsubscript{\beta} radial velocity curve, and therefore is a superior conjunction of the binary system (secondary located between observer and the WD). Accordingly the phase value at \( t_0 \) was set to 0.0. Table 2 gives a summary of the radial velocity fits for H\textsubscript{\beta} and He\textsubscript{ii} 4686 emission line.

After refining the orbital period from spectroscopy, and determining the phase 0.0, the photometric light curve was folded by the corresponding parameters and presented in the lower panel of Fig. 4.

Several conclusions can be made after considering the three curves in Fig. 4 in conjunction with and taking into account common knowledge of Intermediate Polar systems (Patterson 1994; Warner 1995):

- The double peaked Balmer lines are due to the presence of an accretion disk or ring orbiting the primary WD in this IP. RV variations in the wings of lines describe the rotation of the primary of the binary system;
- The S-wave present in the Balmer and He\textsubscript{ii} emission lines is evidence for a hot compact region on the accretion disk;
- From the difference of phases and amplitudes of radial velocities of the wings of H\textsubscript{\beta} and the narrow component of He\textsubscript{ii} we can conclude that the S-wave producing hot spot is located at \( \approx 0.1 - 0.2 \) phase ahead of the superior conjunction. It is difficult to estimate the location more precisely, because the matter in the spot has an intrinsic velocity. It is the usual location of the spot originating from the impact of the mass transfer stream with the accretion disk. However it is also the area which is most commonly heated by the energetic X-ray beam from the magnetically accreting pole on the surface of the WD in IPs (see the sketch in Hellier et al. 1989);
- The hot spot itself is eclipsed by the accretion ring as follows from the phasing of the light curve, the dips in the light curve centered at the phase \( \approx 0.12\phi_{\text{orb}} \). The primary at this phase starts to move toward the observer and the hot spot is on the opposite side of the ring approaching maximum velocity.

From our spectroscopic radial velocity solution, we can determine preliminary values for the basic system parameters of 1 WGA J1958.2+3232. First, from the mass-period and radius-period relations of Echevarria (1983)

\[
\frac{M_2}{M_\odot} = 0.0751P(h)^{1.16},
\]

\[
\frac{R_2}{R_\odot} = 0.101P(h)^{1.05}, \quad 1.4 < P(h) < 12
\]

we estimate the mass and radius of the secondary star as \( M_2 = 0.41 M_\odot \) and \( R_2 = 0.47 R_\odot \).

On the other hand, we can constrain the relation between inclination angle \( i \) versus mass ratio \( q \):

\[
\sin^3(i) = \frac{K_1^2P}{2\pi GM_2} \left( \frac{q + 1}{q} \right)^2
\]

if the mass ratio of the system is known (see Downes et al. 1986; Dobrzycka & Howel 1992). The dependence of \( i \) versus \( q = M_2/M_\text{WD} \) in the range 0.4 up to 0.75 is shown

<table>
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<tr>
<th>Name</th>
<th>( \gamma_0 ) (km s(^{-1}))</th>
<th>( K_1 ) (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>H\textsubscript{\beta}</td>
<td>(-39 \pm 5)</td>
<td>(74 \pm 7)</td>
</tr>
<tr>
<td>He\textsubscript{ii}4686</td>
<td>(-70.2 \pm 15.0)</td>
<td>(197.4 \pm 25.7)</td>
</tr>
</tbody>
</table>
Fig. 7. Trailed, continuum-subtracted, spectra of 1WGA J1958.2+3232 plotted in two cycles. Doppler maps of the emission lines Hβ (left panel), HeⅡ (right panel) in velocity space (Vx, Vy) are given. A schematic overlay marks the Roche lobe of the secondary, the ballistic trajectory and the magnetically funneled horizontal part of the accretion stream. The secondary star and gas-stream trajectory are plotted for K = 74 km s\(^{-1}\) and q = 0.46 in Fig. 6 for the above determined values of K\(_{1}\), \(P_{\text{orb}}\) and \(M_2\).

Meanwhile, the mean mass estimate of 76 white dwarfs in CVs is \(M_{\text{WD}} = 0.86\) \(M_\odot\) (Sion 1999). Webbink (1990) gives statistically average white dwarf masses ratios (q = 0.29) and average masses for all systems (\(M_{\text{WD}} = 0.61\) \(M_\odot\)) below the period gap and (q = 0.64, \(M_{\text{WD}} = 0.82\) \(M_\odot\)) above the period gap. Thus, the possible solutions lie in the narrow range of values.

We attempted to refine these values for 1WGA J1958.2+3232 by constraining Doppler tomograms from observed emission line profiles. Doppler tomography is a useful tool to extract further information on CVs from trailed spectra. This method, which was developed by Marsh & Horne (1988), uses the velocity profiles of emission-lines at each phase to create a two-dimensional intensity image in velocity-space coordinates (Vx, Vy). Therefore, the Doppler tomogram can be interpreted as a projection of emitting regions in cataclysmic variables onto the plane perpendicular to the observers view. We used the code developed by Spruit (1998) to constrain Doppler maps of 1WGA J1958.2+3232 with

<table>
<thead>
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<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>(P_{\text{orb}})</td>
<td>0.18152d</td>
<td>(K_2)</td>
<td>0.47 (R_\odot)</td>
</tr>
<tr>
<td>(P_{\text{rot}})</td>
<td>733.7s</td>
<td>a</td>
<td>1.5 (R_\odot)</td>
</tr>
<tr>
<td>(M_2)</td>
<td>0.41 (M_\odot)</td>
<td>i</td>
<td>35°</td>
</tr>
<tr>
<td>q</td>
<td>0.46</td>
<td>(M_{\text{WD}})</td>
<td>0.9 (M_\odot)</td>
</tr>
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</table>
the maximum entropy method. The resulting Doppler maps (or tomogram) of emission lines of \( H_\beta \), He\textsc{ii} and the blend of C\textsc{iii}/N\textsc{iii} are displayed as a gray-scale image in Figs. 7 and 8. Also in Fig. 7 are displayed trailed spectra of H\textsc{ii} and He\textsc{ii} in phase space and their corresponding reconstructed counterparts. Two features in the maps are distinct: an accretion disk seen as a dark circle extending to up to \(-700\) km s\(^{-1}\) on H\textsc{ii} doppler tomogram and a bright spot detected in all three maps to the left and below the center of mass at velocities \( V_x \approx -250\) km s\(^{-1}\), \( V_y \approx -100\) km s\(^{-1}\) in He\textsc{ii} 4686. Apart from the spot a cometary tail linked to it and extending to \( V_x \approx V_y \approx -500\) km s\(^{-1}\) can be clearly seen on the He\textsc{ii} map. These we identify with the mass transfer stream and its shape was essential for our selection of the ballistic trajectory. A help in interpreting Doppler maps are additional inserted plots which mark the position of the secondary star and the ballistic trajectory of the gas stream. Here we used our estimates of \( P_{\text{orb}} \) and \( M_2 \) with various combinations of \( i \) and \( q \) from Fig. 6 in order to obtain the “best fit” (by simple eye inspection) of the calculated stream trajectory with the gray scale image. Our preferred solution for the inclination is \( i = 35^\circ \). It is marked in Fig. 6 and given in Table 3. Of course other close solutions are applicable. Comparing the location of spots in Doppler maps of He\textsc{ii} and H\textsc{ii} we can actually distinguish two hot spots on the disk (Fig. 7). The elongated spot coinciding in both emission lines is probably caused by the mass transfer stream and the shock of impact with the disk, while the compact dense spot toward negative \( V_y \)’s, seen much better in H\textsc{ii} than in the two other lines, is a result of heating of the disk by the X-ray beam. The C\textsc{iii}/N\textsc{iii} pattern mostly repeats that of He\textsc{ii}, with lower intensity though (Fig. 8).

4. Conclusions

The 1 WGA J1958.2+3232 is found to be a “textbook” Intermediate Polar. It has an orbital period \( P_{\text{orb}} = 4.36 \) above the period gap, as have the vast majority of IPs. It exhibits X-ray and optical coherent pulsations of the order of \( \sim 0.05\) \( P_{\text{orb}} \), undoubtedly originating from asynchronous spin of the magnetic WD in a close binary system. The beat period in optical light is also detectable. This is another characteristic of Intermediate Polars.

Other orbital parameters derived from the assumption that the system obeys the \( P_{\text{orb}} \sim M_2 \) relation for CVs also agree with accumulated data on other IPs and theoretical aspects (Warner 1995; Patterson 1994, see also URL\(^3\)).

The radial velocity curves, the light curve and the Doppler tomography confirm the presence of an accretion ring around the WD and the existence of hot spots caused by heating of parts of the disk by the X-ray beam and from interaction with the mass transfer stream.

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\(^3\) http://lheawww.gsfc.nasa.gov/users/mukai/iphome/members.html#cand