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TIME-RESOLVED SPECTROPHOTOMETRY OF THE EMISSION LINES IN THE GALACTIC X-RAY SOURCE H2252−035[1]

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ABSTRACT

We have carried out time-resolved optical spectrophotometry of the galactic X-ray source H2252−035 for the purpose of studying intensity variations in the high-excitation emission lines. At a time resolution of ~ 2 minutes, the four brightest emission lines (Hα, Hβ, Hγ, and He II λ4686) all showed short time-scale flickering (independent of the observed continuum flickering) and a pronounced orbital period variation in phase with the continuum modulation. We have also detected an orbital period variation in the Balmer decrement in which the ratio Hα:Hβ:Hγ is markedly flatter at the time of the continuum maximum. To fit these observations we propose a two-component model for the line emission region in which one component of the lines comes from the accretion disk as a whole and the other from the more highly photoionized bulge region where the accretion column from the companion star intersects the disk; this second region must have an electron density 10–100 times greater than the rest of the disk to explain the observed decrement variation. The large modulation fraction of the Balmer lines (especially Hγ) suggests that the system has a relatively high inclination, in contrast to prior conclusions reached from modeling of optical photometry data.

Subject headings: X-rays: binaries — stars: dwarf novae

I. INTRODUCTION

The galactic X-ray source H2252−035 has been the object of a concentrated observational effort since being identified with a 13th magnitude optical counterpart with a cataclysmic variable-like spectrum (Griffiths *et al.* 1980). An optical continuum modulation with a mean amplitude of ~ 15% (peak to peak) and a period of 859 s was subsequently identified (Warner 1980; Patterson and Price 1980) along with a 3.59 hour periodicity in both the optical continuum (peak-to-peak amplitude 10%) and in radial velocity shifts of the optical emission lines by Williams and Johns (1980) ($K = 151$ km s^{-1}) and Patterson and Price (1981) ($K = 145$ km s^{-1}); the line shifts suggest that 3.59 hours is the orbital period of the system. Shortly thereafter, measurements of the X-ray flux from H2252−035 were reported which showed a nearly sinusoidal modulation with a period of 805 s and an amplitude (peak to mean) of 40% by White and Marshall (1980) and 100% by Patterson and Garcia (1980). Finally, an 805 s modulation of the optical continuum with a mean amplitude of 0.02–0.04 mag was reported by Warner and Donoghue (1980). Since the 859 s periodicity corresponds to the beat frequency between the X-ray and orbital periods, it has been interpreted as reprocessing of the X-ray flux into optical emission in some region of the system which is rotating with the orbital period and heated by beamed X-ray emission from the compact star (the star must be spinning in a prograde sense to produce the observed beat frequency). Two possibilities have been discussed for the reprocessing site: Patterson and Price (1981) suggest that it is the heated atmosphere of the companion star, whereas Hassall *et al.* (1981) argue that the bulge region where the accretion column strikes the disk is a more likely site. In either event, the apparent nonsynchronous rotation of this system offers an excellent opportunity to study the source of the high-excitation emission lines, since one may examine them for variations with each of the three periods and thereby distinguish between various source regions in the system.

II. OBSERVATIONS

To study the intensity variations in the emission lines, we have observed H2252−035 with the 120″ (3 m) Shane telescope and image dissector scanner at Lick Observatory on 1980 September 9/10 and on 1981 September 20/21. These observations consisted of a series of 2 minute integrations covering a range of 2400 Å at 10 Å resolution for a period of approximately 2 hours each night; the 2 minute integration time was

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chosen as a trade-off between achieving a high signal-to-noise ratio in a single emission line and resolving the shorter 13–14 minute continuum pulse periods. The data have been reduced by standard techniques through observations of wavelength and flat-field calibration lamps and flux standard stars from Stone (1977). In the 1980 observations, two different grating tilts were employed to cover a wide spectral range (3700–8300 Å). Sufficient integration time was employed to obtain a high signal-to-noise ratio spectrum over the entire band. In the 1981 observation, a constant grating tilt covering the lines Hα–Hγ was used to investigate possible orbital period variations in the Balmer lines which had been seen in the 1980 data.

A composite spectrum from the two years' observations summed over 4 hours of observations at different grating tilts is plotted in Figure 1: no significant spectral features have been identified longward of 6700 Å, other than atmospheric O_2 and H_2O bands. A number of weak emission lines of He I and He II are positively identified in the spectrum: the wavelengths and intensities of these lines are listed in Table 1. There is no evidence in any of these observations for the absorption feature at 5090 Å suggested by Warner (1980), but the spectrum shows clearly the emission blend of C III/N III at 4640–4650 Å which has been tentatively identified by several authors. This feature appears at a central wavelength of 4640 Å and is broader than the Balmer lines. This suggests that it is N III λ4640 rather than C III λ4650, but each of these features is a blend of several weaker lines and the observed feature may therefore contain some C III emission as well.

In Figure 2, the time sequence of data from the series of 2 minute integrations obtained during the 1981 observation is plotted: shown are the visual magnitude and the absolute intensities of the four brightest emission lines. The error in the measurement of the visual magnitude from counting statistics in a 2 minute integration is less than 0.2%; the average error in the measurement of an emission line intensity from counting statistics is 9%, and the error introduced by the extraction of the line intensities from the continuum emission is estimated to be $\lesssim 10\%$ (sample error bars are plotted in Fig. 2). The 14.3 minute pulsation appears clearly at two points in the V magnitude data and is otherwise quite variable in amplitude, ranging from 20% peak-to-peak at 9:13 UT to less than 3% later in these data. It is significant that the line intensities do not appear to follow this

TABLE 1

H2252−035 Emission Line Intensities in Summed Spectrum

Line	Wavelength (Å)	Intensity[a] (ergs cm^{-2} s^{-1})	Equivalent Width (Å)
He I	6678	0.20	1.86
Hα	6563	1.65	14.1
He I	5875	0.35	2.55
He I	5015	0.16	0.77
He I	4921	0.18	0.84
Hβ	4861	1.43	6.58
He II	4686	0.98	4.25
N III/C III ...	4640	0.26	1.12
He I	4471	0.22	0.90
Hγ	4340	0.75	3.07
Hδ	4101	0.53	2.87
Hϵ............	3970	0.27	1.60
Hζ............	3889	0.24	1.46

[a]All values multiplied by 10^{-13}.

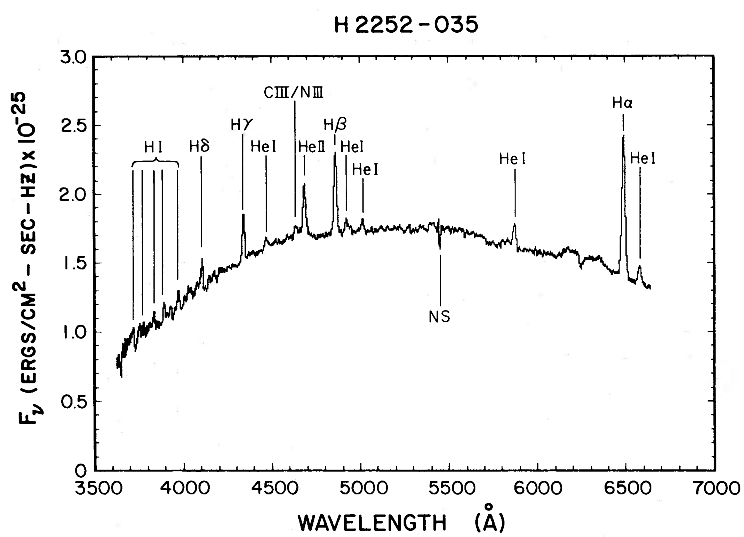

FIG. 1.—Composite ~4 hour spectrum of the galactic X-ray source H2252−035 taken with the Lick Observatory 120 inch (3 m) telescope, summed from two separate observations 1 year apart.

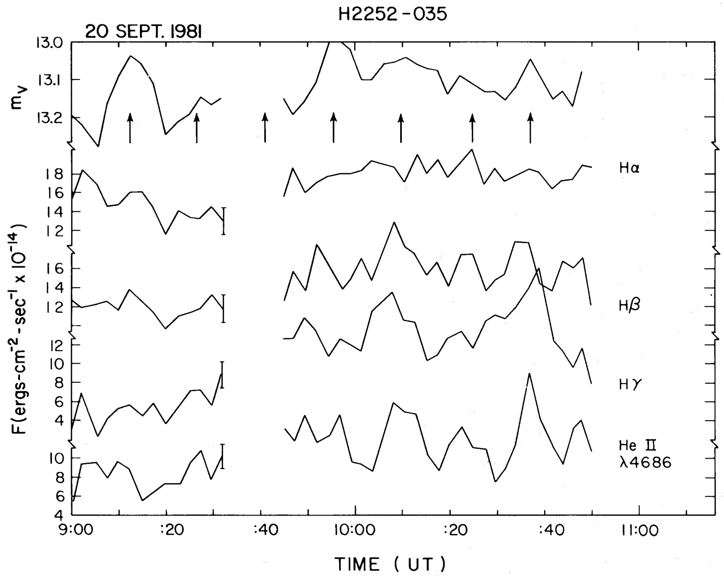

FIG. 2.—Real-time plot of the continuum and the four brightest emission line intensities observed during the 1981 September run on the Lick 120 inch (3 m) telescope. Phase maximum in the 3.6 hour period is calculated to occur at 10:02 UT, and the expected times of the 14.3 minute pulsations in m_v are marked with arrows with phase zero determined by the peak near 9:13 UT. Note the factor of 3 variation in the Hγ intensity over the course of this run.

continuum pulsation: although all three Balmer lines show increases of ~20% in phase with the 9:13 UT continuum pulse none of the lines increase in phase with the 9:57 UT continuum pulse, and the variations at 9:13 UT are at the 2 σ level in a 2 minute measurement of the line intensities. The line intensities all show a clear increase (in phase with the continuum) toward the calculated orbital period maximum at 10:02 UT, and they exhibit large amplitude flickering which appears independent of the continuum variations but is often coincident among several emission lines; e.g., the increases observed near 10:10 and 10:37 UT appear strong in the Hβ, Hγ, and He II lines. Warner (1980) has reported observing much more extreme variability in which the H and He lines at times disappeared completely: there is no evidence in the present data for such variability, as can be seen in Figure 2.

III. PHASING WITH PHOTOMETRIC PERIODS

To investigate in more detail the periodic variations of the emission lines, we have folded the measured intensities of the four brightest lines on the known periods of 13.6 minutes, 14.3 minutes, and 3.6 hours. We find phase 0.0 (corresponding to the continuum maximum) for the two shorter periods to be at 9:13 UT, where the largest ~14 minute variation was observed in the real time data. The phase of the 3.6 hour period was reconstructed from an updated ephemeris (T_{max} = JD 2,444,428.873 + 0.149624 ± 3 E; Córdova, Mason, and Horne 1982) based on photometric observations in 1981 August. The folded data showed clear continuum modulations on all three periods, although the data did not cover a complete 3.6 hour cycle as would be necessary to completely separate possible beating effects between the two shorter periods. Peak-to-peak continuum variations in the Johnson V band of 5%, 12%, and 15% were seen, respectively, from the data folded on the 13.6 minutes, 14.3 minutes, and 3.6 hour periods. Typically 5–6 spectra were summed per bin, giving an average error in the line intensities of ~5%. However, the observed scatter in the data folded on the 13.6 and 14.3 minute periods was in some cases significantly greater than 5% (possibly due to the observed flickering of the lines), and none of the lines showed sinusoidal modulations on these shorter periods to within these errors. Best fit sine curves to the line intensity data folded on the three periods have been determined by a least squares routine: the results of these fits are given in Table 2, which lists the line intensities and semiamplitudes of the sine curves which best fit the data.

In contrast to the shorter periods, pronounced line variations appeared when the data were folded on the 3.6 hour period. These data have been summed into 14 minute bins (to remove any bias from variations with the shorter periods) and are plotted in Figure 3, which combines data from the two observations one year apart. Only the three lines for which full phase coverage exists have been fit with sine curves, and their amplitude ranges from ±23% for Hβ to ±53% for Hγ. The difference in phase between the maxima in the three Balmer lines and the calculated phase 0.0 is within the

TABLE 2

OBSERVED SINUSOIDAL SEMIAMPLITUDES IN H2252−035 LINE INTENSITIES

Period	V Band	Hα	Hβ	Hγ	He II (λ4686)
13.6 minutes (1981 data) ...	±2.5%	±(≤1%)	±(≤7%)	±(≤10%)	±(≤9%)
14.3 minutes (1981 data) ...	±6%	±(≤2%)	±(≤10%)	±(≤14%)	±(≤13%)
3.6 hours (1980 data) ...	...	...	±12%	±29%	±4%
3.6 hours (1981 data) ...	±7.5%	±19%	±14%	±50%	±30%
3.6 hours	...	...	±23%	±53%	±33%

uncertainty in the ephemeris used to determine zero phase, but He II reaches a maximum near phase 0.17, which may be a significant difference and would suggest that this emission comes from a different region in the system than the Balmer lines. The good fit of the lines to sine curves suggests that the modulation is due to the rotational motion of at least part of the emission line region in and out of our line of sight, rather than being caused by an eclipse or obscuration of part of this region: such a modulation is consistent with the identification of reprocessing in this source. It is also significant to note that the ratio of the observed Balmer line intensities varies with this period; the decrement ratio Hα:Hβ:Hγ ranges from 1.15:1.00:0.81 at phase maximum to roughly 1.2:1.00:0.38 at phase minimum ("roughly" since the Hα intensity was extrapolated from phases 0.25 and 0.75). The observed factor of two variation in the ratio Hβ:Hγ implies a considerable difference in excitation between the emitting regions which are observable at phase minimum and phase maximum. Furthermore, the ratio Hβ:Hγ plotted on the 3.6 hour period appears roughly sinusoidal in shape, suggesting that it also is a geometric effect produced by the rotation of the system.

Care must be taken in interpreting the magnitude of the line and Balmer decrement variations, as there is some evidence that these were different on the two nights ~1 year apart. For example, from Figure 3 it is clear that the 1980 He II data can be fitted by a much lower amplitude variation than would be derived from fitting all the He II data. In addition, other workers are currently reporting an observation during which the Balmer decrement did not vary within their measurement uncertainty (Córdova, Fenimore, and Mason 1982). For this reason, we have performed separate fits to the 1980 and 1981 data, which are also listed in Table 2. The He II line shows the biggest difference between the two years, being more intense and much more variable in the 1981 data; the Hβ line appears to have been slightly more intense in 1981; and Hγ was more highly variable. However, all the lines varied on the orbital period each time they were observed, and the ratio Hβ:Hγ showed an orbital period variation of ±20% in the 1980 data (taken alone) and of ±40% in the 1981 data.

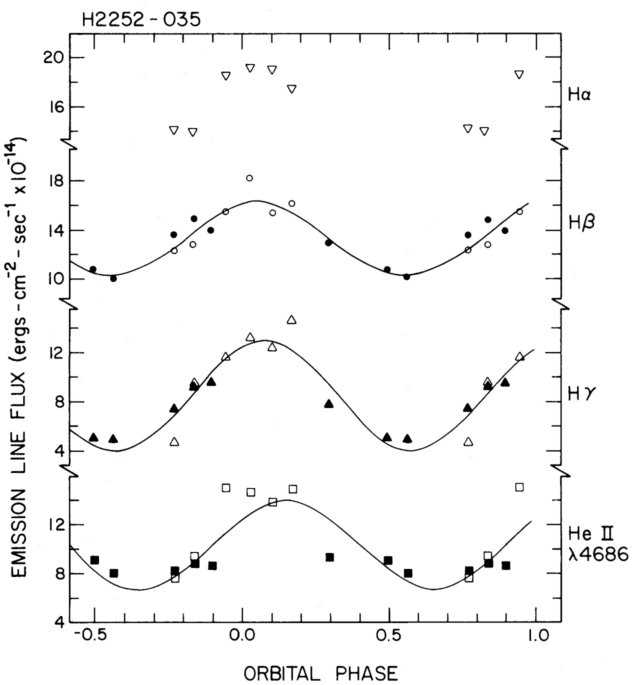

FIG. 3.—Intensities of the four brightest emission lines folded on the 3.6 hour continuum period, as described in the text. The Hα line has not been fitted to a curve as no data were taken coincident with the other lines near phase minimum. The solid characters give the data from the 1980 September observing run, and the hollow characters data from the 1981 September run. Each point represents a 14 minute summed integration.

IV. DISCUSSION

It is interesting that the emission line intensities at times vary with 2–3 times the amplitude of the continuum variation on the 3.6 hour period, but do not vary with an upper limit comparable to the strong continuum variation on the 14.3 minute period. The width of these lines (FWZI ≈ 1100 km s^{-1}) suggests that the bulk of the line emission arises from the accretion disk rather than the atmosphere of the companion star (Hassall *et al.* 1981); the observed radial velocity shifts of the emission lines are then interpreted as representing motion in the outer regions of the accretion disk, rather than the atmosphere of the companion star. Our present observations therefore require us to identify some component of the system, probably associated with the accretion disk, which (1) contributes a large fraction of the observed emission line flux (2) shows a rotational modulation with the proposed orbital period, and (3) exhibits a markedly flatter Balmer decrement than the disk as a whole.

Two lines of evidence point to the identification of this variable emission-line region with the bulge on the accretion disk produced at the point where the accretion column strikes the disk. The first is based on a comparison of our observed H emission-line intensities with the extensive theoretical modeling of hydrogen emission line regions by Drake and Ulrich (1980). These authors have calculated the expected Balmer decrements as a function of electron density N_e between 10^8 and 10^{15} cm^{-3}, electron temperature T_e between 5×10^3 and 10^5 K, and optical depth τ at Hα between 1 and 4×10^2. Although the range of possible solutions is large, only a relatively small subset of high-density models fits the shallow Balmer decrement observed in H2252$-$035. This subset contains good model fits to the observed decrement only for values of $N_e \gtrsim 10^{12}$ cm^{-3}, and the range of especially flat decrement values (Hγ:Hβ greater than 0.7) corresponds to $N_e = 10^{13}$–10^{14} cm^{-3} in most of the models. The range of temperature for the flat decrement models is $10^4 \lesssim T_e \lesssim 10^5$, and good fits are obtained for a range of $\tau_{\mathrm{H}\alpha} \geq 10$. Furthermore, the decrement ratios change slowly when $\tau_{\mathrm{H}\alpha}$ is varied over this range of parameters but rapidly when T_e varies over the range 5×10^3 to 10^4 and especially when N_e varies over the range 10^{12} to 10^{14}. The simplest way to produce the observed flattening of the Balmer decrement is thus by introducing a region of higher T_e (by several thousand K) and higher N_e (by 10–100 times) which is most directly visible at the time of photometric maximum in the 3.6 hour cycle and rotates in and out of the field of view.

The second line of evidence implicating the accretion disk hot spot as this high T_e and N_e region of line emission comes from modeling of the conditions expected in accretion disks as a result of the balance between heating (by radiation from the compact star) and radiative cooling. The work of Williams (1980) suggests that Balmer line emission should be produced mainly in the cooler outer layers of accretion disks, which are maintained at temperatures greater than 6000 K and are optically thin to continuum emission but optically thick to Balmer line emission. The observation of a higher pulsation fraction on the 3.6 hour period in the Balmer lines than in the optical continuum is certainly consistent with the emission region being optically thin to the continuum and optically thick to the lines. Furthermore, the bulge on the accretion disk is expected to be confined to the outer regions of the disk and would intercept a greater fraction of the X-ray and EUV radiation from the compact star than other places along the disk. This in turn should lead to a hotter, more highly photoionized region along the inner side of the bulge, which is consistent with the observed phasing of the increased line and continuum emissions, regardless of whether the continuum pulsing is due to reprocessing in the hot spot or in the atmosphere of the companion star. The amplitude of the Balmer line pulsations is thus interpreted as a measure of the optical thickness of this region as well as a function of the inclination of the system, and the line pulsations may be expected to vary in amplitude as a function of the mass transfer rate and the resulting size and thickness of the bulge on the accretion disk. This further removes the constraint of a low inclination angle for H2252$-$035 discussed by Hassall *et al.* (1981), which is required if the continuum reprocessing occurs in the secondary star atmosphere; in fact, the large observed line pulsation fraction indicates that the inclination of the system is high.

It should be noted that Williams (1980) was not able to reproduce He II line emission in his modeling of the normal outer regions of accretion disks; he suggested that the He II line emission probably comes from the inner regions of the disk or the hot spot. This is consistent with our data if the bulge on the disk is optically thick in the He II λ4686 line as well as in the Balmer lines. Finally, the identification of a large fraction of the line emission from the hot spot implies that there may be a narrow component of the emission lines varying both in wavelength and in strength with the orbital period, in addition to the broad component observed from the disk as a whole. As our data were taken with large apertures to insure good photometry the resulting spectra were of insufficient resolution to detect such a narrow emission line component, but its detection offers a test for the proposed explanation of the orbital variations observed in the emission line strengths and Balmer decrement.

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