MULTIWAVELENGTH OBSERVATIONS OF EXO 0748–676. II. EMISSION-LINE BEHAVIOR

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ABSTRACT

We present optical and ultraviolet spectra, light curves, and Doppler tomograms of the low-mass X-ray binary EXO 0748–676. Using an extensive set of 15 emission-line tomograms, we show that, along with the usual emission from the stream and “hot spot,” there is extended nonaxisymmetric emission from the disk rim. Some of the emission and Hα and Hβ absorption features lend weight to the hypothesis that part of the stream overflows the disk rim and forms a two phase medium. The data are consistent with a 1.35 M☉ neutron star with a main-sequence companion and hence a mass ratio q ≈ 0.34.

Subject headings: accretion, accretion disks — binaries: closestars: individual (UY Vol)

Online material: color figures

1. INTRODUCTION

The low-mass X-ray binary (LMXB) EXO 0748–676 was first recognized as a transient X-ray source by EXOSAT in 1985 (Parmar et al. 1985), and an optical counterpart, UY Vol, was soon associated with it (Wade et al. 1985). Rather than returning to a quiescent state, the system has persisted in outburst since then and fits the typical pattern of the “persistent” class of objects, showing extended periods of activity lasting several years before switching off for a similar period (White et al. 1995). This intriguing behavior suggests that such systems are switching between two metastable states in a situation analogous to that of the Z Cam subgroup of the dwarf nova (DN) group of cataclysmic variables (CVs).

The outbursting behavior of DNe can be understood in terms of the accretion disk in the system being able to exist in two states (“hot” and “cold”) characterized by high (or conversely low) ionization, viscosity, mass throughput, and luminosity (see, e.g., the review of Warner 1995). Systems switch from the low state to the high at a critical surface density (or equivalently temperature), giving rise to high-luminosity outbursts. Due to an hysteresis effect, the disk switches back to the low-viscosity state at a second, lower, critical surface density, and the disk then refills with material from the secondary. Z Cam stars exhibit “standstills” where outbursts are suspended. During these periods, the disk is maintained in a high-viscosity state. Transient LMXBs can be seen as the analogs of DNe with the central white dwarf replaced by a neutron star or black hole (see, e.g., the review of King 2006). The model above must be modified to account for the effects of X-ray irradiation. This will tend to stabilize systems in the high state by reducing the critical mass transfer rate for transition back to the low state and thus lengthen the duration of outbursts (van Paradijs 1996; King et al. 1997). Like Z Cam stars, the persistent LMXB systems have a sufficient mass transfer rate to maintain extended periods of high luminosity, and the smaller size of the system makes this, rather than the low state, the default configuration. Occasionally (in evolutionary terms), they transition to a low-viscosity state.

The review of King (2006) explains how the observed luminosity of EXO 0748–676 implies that the neutron star has accreted ~1025 kg since the “turn-on” in 1985. Given that the maximum disk mass that would have allowed the disk to exist in the low state is ~1.3 × 1024 kg, this confirms that the system must currently be accreting in a stable “hot” configuration. The periods of reduced mass transfer might plausibly be ascribed to starspots on the secondary (King & Cannizzo 1998).

Systems like EXO 0748–676 hold out the prospect of allowing us to probe the nature of the (in)stability mechanism. The understanding gained could then be transferred to more volatile systems.

EXO 0748–676 has an inclination that is well constrained by its light curve. The inclination must be high enough that the disk rim can generate the X-ray dips and eclipses that are observed to recur on the 3.82 hr orbital period. On the other hand, it must also be low enough that the X-ray eclipse is sharp and brief, indicating that the neutron star is visible outside of eclipse. Quantitatively, this translates to the range 75° < i < 82° (Parmar et al. 1986; Hynes et al. 2006). There is 4% residual X-ray flux during eclipse attributed to scattered emission by a small optically thin accretion disk corona (ADC; Parmar et al. 1986).

Probably the most natural place to seek the origin of the dips is the disk rim. Analysis of the gas dynamics (Flannery 1975; Lubow & Shu 1975, 1976) indicates that the impact of the mass transfer stream on the disk will cause a thickening of the rim. Following the suggestion of Mason et al. (1980), modeling of the X-ray light curve of 2A 1822–371 (White & Holt 1982) supported the need for such a rim structure. However, work by Frank et al. (1987) suggested that the absorbing material might actually be closer to the primary from material overflowing the disk rim. Simulations by Armitage & Livio (1996) showed that the interaction of the stream and disk did not produce enough disk thickening to prevent material flowing above and below the disk.
hot spot, following a near-parabolic path and impacting at a locus
of points across the disk face. This absorbing material would
exist in a two-phase state as a result of an ionization instability:
cool neutral clouds would coexist with a hot, ionized intercloud
medium (Frank et al. 1987). The crucial difference between the
two models is the relative thickness of the stream and disk. In a
model that considers only gravity and gas pressure, the stream
will spread to have a vertical height larger than the disk and would
be expected to be able to flow over the disk surface. The disk would
only exhibit a limited thickening downstream from the hot spot. In
contrast, the contemporary incarnation of the thick-rim model in-
vokes X-ray irradiation to heat the disk rim and cause it to puff up.
In this case, the stream would be unable to significantly overflow
the disk. However, this picture suffers from the difficulty that to puff
up the disk to a suitable height would require X-ray temperatures in
the disk midplane. X-ray irradiation could only achieve this if the
disk were optically thin to X-rays, but if this were so, the rim
would not be able to act to obscure X-rays and cause dips.

We are aware of Doppler tomograms having previously been
published for seven X-ray binaries in a high state: 2A 1822–371
(Harlaftis et al. 1997; Casares et al. 2003), Her X-1 (Still et al.
1997; Vrtilek et al. 2001), XTE J2123–058 (Hynes et al. 2001),
Sco X-1 (Steeghs & Casares 2002), AC 211 (Torres et al. 2003),
and XTE J1118+480 (Torres et al. 2004). This work presents a
detailed study as part of a multiwavelength campaign using the
Hubble Space Telescope (HST), Rossi X-Ray Timing Explorer
(RXTE), CTIO, and Gemini with contemporaneous VLT and
Magellan observations. In Paper I (Hynes et al. 2006), we stud-
ied the burst properties of EXO 0748–676 using rapid spectro-
scopic and photometric data. Here we study the accretion structure
using spectra, light curves, and Doppler tomograms from several
optical and ultraviolet observations.

2. OBSERVATIONS

2.1. HST

HST observations of EXO 0748–676 were obtained on 2003
February 18–19 using the Space Telescope Imaging Spectrograph
(STIS; Profitt et al. 2002). The observations were timed such that
the target was within the continuous viewing zone (CVZ). Con-
sequently, we were able to observe over about 9 hr with only small
gaps for wavelength calibrations and mode changes. This covered
two complete binary orbits. Our coverage is summarized in Table 1.

All observations used the MAMA UV detectors in TIMETAG
mode, yielding a stream of detected events with 125 µs preci-
sion, which could be used to reconstruct spectra for any desired
time interval. Most observations concentrated on the far-UV,
using the G140L grating. Two short observations of the near-UV
region, using the G230L grating, were also obtained.

The G140L grating observations had a spectral dispersion of
0.6 Å pixel$^{-1}$, which, combined with a resolution element
varying with wavelength, gave a spectral resolution of 1.02 Å at
1200 Å, 0.90 Å at 1500 Å, and 0.84 Å at 1700 Å. Similarly, the
G230L grating had a dispersion of 1.58 Å pixel$^{-1}$ yielding a
spectral resolution of 3.5 Å at 1700 Å and 3.3 Å at 2400 Å.

All HST spectra were reduced with the standard CALSTIS
pipeline software. Where appropriate, we used INTTAG to divide
TIMETAG exposures into subexposures before applying the
CALSTIS calibration. For the near-UV (G230L) observations, we
found no reason to change the default settings. The G140L far-UV
parameters are not adequate to precisely describe this. Therefore,

![Fig. 1.—Compilation of the mean-calibrated spectra from the HST and CTIO data sets.](image-url)
we adjusted the tilt to fit better the two-dimensional spectra and moved the background regions closer to the source spectrum. This greatly improved the LyC extraction, although some small residuals are still visible.

The mean HST spectra are shown in Figures 1, 2, and 3.

2.2. CTIO 4 m Blanco

Optical spectroscopy was obtained on 2003 February 14–15 using the R-C grating spectrograph (RCS) on the 4 m Blanco Telescope at the Cerro-Tololo Interamerican Observatory (CTIO). The KPGL1 grating was used with a wavelength coverage of 3600–6620 Å. The combination of the 1′3 slit width, a spectral dispersion of 0.95 Å pixel\(^{-1}\) and a spatial scale of 0.5 arcsec pixel\(^{-1}\) gave a spectral resolution of 2.47 Å. Initial data reduction used standard IRAF\(^{10}\) techniques for bias removal, flat-fielding, and optimal extraction of the spectra.

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\(^{10}\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
The slit was rotated to include another star on the slit, and this was used for both relative flux calibration and relative wavelength calibration. Owing to technical difficulties, we were unable to intersperse the target observations with arc calibrations and so wavelength calibration was done only using HeNeAr arcs from the beginning of the first night, with subsequent offsets derived using absorption lines in the spectrum of the comparison star. The comparison star was calibrated relative to the spectrophotometric standard EG21 (Hamuy et al. 1992, 1994) using an observation taken at low air mass with a wide slit. All object spectra were then calibrated relative to this.

The mean spectrum from both nights of observation is shown in Figures 1 and 2.

2.3. VLT

Optical spectroscopy was also obtained on 2003 February 7 and 2003 February 28 with the Very Large Telescope (VLT) at Cerro Paranal, Chile. The first night of observation used the FORS2 spectrograph and 14000 V grating with wavelength coverage 4540–5840 Å and mean dispersion of 0.637 Å/pixel\(^{-1}\); the second night the 600 R\(g\) grating with 5080–8395 Å coverage and mean dispersion of 1.62 Å/pixel\(^{-1}\). Both sets of observations used a slit width of 0.4′, making slit losses significant and absolute flux calibration unreliable. With a spatial scale of 0.125 arcsec pixel\(^{-1}\), this gave a spectral resolution of 2.04 Å for night 1 and 5.18 Å for night 2.

Initial data reduction was again carried out using IRAF. He II and HgCd arc lines were obtained during the day before and after the observations and interpolated through the night.

The mean spectrum from both nights of observation is shown in Figure 2.

2.4. Magellan

Two spectra were obtained with the 6.5 m Walter Baade, Magellan Telescope at Las Campanas Observatory, Cerro Manqui, Chile, on 2003 December 14 and 15. The IMACS instrument was used in f/4 configuration with a 0′.7′ slit and an 8k × 8k CCD mosaic detector operating in 2 × 2 binning mode. The low-resolution spectrum was obtained using the 300 grating with a range of 3410–9350 Å and a 1.5 Å/pixel\(^{-1}\) image scale, giving 4.3 Å resolution. The higher-resolution spectrum was obtained using the 600 grating with a wavelength range of 3730–6830 Å, a 0.76 Å/pixel\(^{-1}\) image scale and 2.0 Å resolution. Data reduction was carried out using PAMELA software. Both spectra are plotted in Figure 2.

### 2.5. Archival International Ultraviolet Explorer Spectra

Three spectra of EXO 0748–676 were obtained using the low-resolution short-wavelength prime camera (SWP) in 1990–1991. As these have not been published previously, we extracted the NEWSIPS reprocessed spectra (Nichols & Linsky 1996) from the archive for comparison with our new data. We constructed an exposure time weighted average. This is based on ~5 binary orbits and so should adequately represent the mean spectrum in 1990–1991. The extracted spectra are plotted alongside our HST spectra for comparison in Figure 3.
mention are moving features, present in the Balmer lines, that originate within the binary. These will be discussed more thoroughly in § 3.3.

Equivalent widths were measured for all the lines in Table 2 in each data set where they were present. The values are summarized in Table 3. Where there was significant phase coverage, each set of data was binned by phase with variance weighting and then a mean spectrum derived with equal weighting for each phase bin. Error estimates were derived by making the measurement 10 times with independently selected continuum regions in each case.

### 3.2. Light Curves

Light curves were generated for several of the emission lines considered above having subtracted a polynomial fit to the local continuum in each case. These are plotted in Figure 4.

The CTIO Hα data presents an overall smooth symmetric light curve. Surprisingly, this appears to have two peaks at φ = 0 and 0.25 with a hint of brief absorption episodes either side of the former. The Hβ light curve also peaks around φ = 0 but the rising part of the light curve appears steeper than the descending section. At minimum light, the flux completely disappears as a result of the absorption feature that moves across the line profile.

In contrast to the hydrogen Balmer lines, the He ii λ4686 line reaches a broad peak at around φ = 0.5 and reaches a sharper minimum in the range φ = 0.9–0.0. The He ii λ1640 and He ii λ5412 light curves show very little coherent behavior and much scatter and the C iii λ1176 light curve does not show any clear orbital modulation.

The four light curves N v λ1240, O v λ1371, Si iv λ1400, and C iv λ1549 show similar behavior. Each light curve peaks in the range φ = 0–0.1 and reaches a minimum around φ = 0.5. However, the orbital modulation is relatively weak in each case. The material producing all six of the ultraviolet lines appears to be visible at all phases and uneclipsed. This suggests that rather than being distributed throughout the disk, these high-ionization

### Table 3

| Line         | VLT1 | CTIO | VLT2 | Mag. 300 | Mag. 600 | HST |
|--------------|------|------|------|----------|----------|-----|
| Hα           |      |      |      |          |          |     |
| Hα without absorption |      |      |      |          |          |     |
| Hβ           | 0.249(38) | 1.008(11) |      | 2.746(65) | 4.061(94) |     |
| Hβ without absorption | 1.019(5) | 1.273(10) |      | 4.009(36) |          |     |
| He ii λ4686  | 4.607(23) | 3.899(8) |      | 4.662(38) | 5.03(12)  |     |
| He ii λ5412  | 1.597(7) | 1.565(20) | 1.462(5) | 2.336(32) | 1.870(21) |     |
| He ii λ1640  |      |      |      |          |          | 6.511(18) |
| C iii λ1176  |      |      |      |          |          | 3.549(10) |
| C iv λ5490   |      |      |      |          |          | 18.82(19)  |
| N v λ1240    |      |      |      |          |          | 16.52(10)  |
| O v λ1371    |      |      |      |          |          | 2.212(4)   |
| Si iv λ1400  |      |      |      |          |          | 4.442(44)   |
lines arise from specific regions that are never hidden by the secondary.

Crampton et al. (1986) published a broadband $B$ light curve and
three equivalent width line light curves. Their H$\beta$ results are
close to those presented here. However, their He $\Pi \lambda 4686$ plot
contrasts strongly with ours; being similar to the H$\beta$ behavior.
The He $\Pi \lambda 4686$ results derived from our CTIO data appear to be
in antiphase to this and eclipse in a similar way to the broadband
light curve. Since the earlier results using equivalent width are
effectively normalized to the continuum, their He $\Pi \lambda 4686$ light
curve probably represent the behavior of the underlying contin-
num rather than the line behavior itself.

3.3. Trailed Spectra

Trailed spectra generated for all the emission lines considered
above (summarized in Table 2) are given in Figures 5 and 6. The
continuum in the region of each line was fitted with a low-order
polynomial and subtracted off. Normalizing the flux by their
continuum contributions before subtraction produced no significant differences in the results. The orbital phase was calculated using the ephemeris of Wolff et al. (2002). These data have all been binned by orbital phase and are shown over two cycles with some smoothing. A sine wave with an amplitude of 750 km s\(^{-1}\) has been overplotted on each trail to guide the eye and aid in cross-comparisons. The amplitude was chosen to match the clearest observed S-wave that arises from the O\(^{v}\) line.

The O\(^{v}\) S-wave is so strong as to drown out the broader structures arising from the disk. The He\(^{ii}\) \(\lambda 1640\) line shows a clear hybrid structure with an S-wave matching the O\(^{v}\) kinematics superimposed on a double-peaked profile that arises from the accretion disk. The more complex emission of the other UV lines makes it more difficult to pick out discrete features. However, it is possible to identify the S-wave in the other UV lines, with the exception of C\(^{iii}\) 1176, using SAOIMAGE DS9 (Joye & Mandel 2003) image visualization routines. The N\(^{v}\) line is worthy of note as the S-wave appears superimposed on a constant velocity profile close to the line center. In the optical data, there also appears to be enhanced emission along this S-wave at certain phases in the VLT2 He\(^{ii}\) \(\lambda 5412\) trailed spectra.

Looking closely at the H\(^{\alpha}\) and H\(^{\beta}\) trailed spectra, there seem to be two absorption components superimposed on the emission lines. An S-wave component is clear in the VLT2 H\(^{\alpha}\) data, less visible in the CTIO H\(^{\alpha}\) data and also in the phase range 0.5–1.0 for the two H\(^{\beta}\) data sets. In the H\(^{\alpha}\) data in particular, these align with the kinematics of the O\(^{v}\) emission feature while the VLT1 H\(^{\beta}\) absorption traces a lower amplitude sinusoid. There is also a clear constant velocity component in the CTIO H\(^{\beta}\) data in the 0–0.4 range and possibly also in the VLT1 H\(^{\beta}\) and CTIO H\(^{\alpha}\) data.

Sample spectra showing the motion of the absorption features from the VLT data sets are shown in Figure 7. In an attempt to increase the signal-to-noise ratio, the H\(^{\beta}\) spectra are formed from an average of four individual observations leading to a degree of orbital smoothing.

In H\(^{\alpha}\), the absorption is clearly visible to the long-wavelength side of the emission line at \(\phi = 0.06\) and \(\phi = 0.98\). At \(\phi = 0.51\) the absorption is appearing on the blue side of the profile. At \(\phi = 0.25\) and \(\phi = 0.75\) the absorption is closer to the line center but predominantly affecting the red peak of the double-peaked disk profile. In H\(^{\beta}\), the broad absorption feature is just apparent on the red wing at \(\phi = 0.02\). The absorption moves into the double-peaked disk profile and appears to be slightly to the blue side of the line center at \(\phi = 0.67\). By \(\phi = 0.8\) the feature is moving back to the long wavelength side of the profile. This behavior is consistent with that shown by the only other two published spectra for this object that we are aware of (Crampton et al. 1986). The similarity of the kinematics of the H\(^{\alpha}\) absorption and high-ionization emission lines suggests that they arise from the same region. To achieve this would require the plasma to exist in both hot and cold phases simultaneously. Such a situation was envisioned in the overflowing stream model of Frank et al.
(1987) with cold blobs embedded in a hotter low-density gas. However, the temperatures required in that model are much higher than that which would produce the lines we observe. It is likely, therefore, that another mechanism is at work. For example, the temperature separation may arise from differences in the efficiency of cooling between denser and rarer regions. The behavior as arising from an extended region of absorbing material along an overflowing stream. For early phases, the absorption would preferentially pick out that part of the stream which the point where the overflowing stream merges with the outer disk. Close examination of our optical and UV spectra show no convincing evidence for the presence of either feature in this system.

3.4. Doppler Tomograms

We have used the unsmoothed trailed spectra to generate Doppler tomograms using the maximum entropy technique of Marsh & Horne (1988). The tomograms formed from the optical observations are shown in Figure 8 and those from the HST observations in Figure 9. Markings on the plots were generated using $q = 0.34$, $M_1 = 1.35 M_\odot$ and $i = 75.5^\circ$ (model 3 of Paper I). The velocities of the centers of mass of the system and of the two stars are marked with crosses. The Roche lobe of the secondary and the Keplerian velocities at the expected edge of the disk and at the circularization radius are also plotted. Two trails are also indicated in the figure. The solid line shows the expected ballistic trajectory of material leaving the L1 point. The dot-dashed line shows the Keplerian velocity at each point that the ballistic stream would pass through.

The H$\alpha$ and H$\beta$ lines show consistent behavior between both the CTIO and VLT data sets with emission confined to lower velocities than we would expect for any disk material. Both lines, however, suffer from the effects of the absorption feature that mean we must treat the derived tomograms with caution. Absorption violates an assumption in the reconstructive technique: that the observed flux is positive.

The He $\alpha$ 4686 line is similar in both VLT and CTIO data sets with emission close to the ballistic stream, although the CTIO
tomogram has it in a position also consistent with the edge of the
disk. The He\n\textsc{ii} \\lambda 5412 tomograms are all rather noisy reflecting
the weakness of the line and difficulty in effecting an accurate
continuum subtraction. Although they all show scattered knots
of emission about the disk, the lack of reproducibility strongly
suggests that these are noise artifacts. Each of them, however,
does show emission at some point along the ballistic stream.

It is not unusual for low levels of emission to appear in low-
velocity regions of close binary tomograms, particularly when
there is limited velocity resolution (e.g., Torres et al. 2002, 2004;
Hynes et al. 2001; Kaitchuck et al. 1994). The filling effect is
most prevalent in our data in the CTIO data set, even in the H\textalpha
and H\beta maps. However, the CTIO data has the middle velocity
resolution of the three optical data sets used in constructing the
maps. The question arises then as to whether a real change oc-
curred in the accretion flow structure between the VLT1 and
CTIO observations and back again before the VLT2 observation.
If this is accurately mapped gas, we must seek an origin for the
roughly axisymmetric, low-intensity, low-velocity emission. If
the material were in the disk, it would clearly be sub-Keplerian.
However, if the material were to have a significant motion out of
the plane, the consequent projection of velocity could map it into
the low-velocity region. Such motion might arise from a weak
disk wind, for example. Alternatively, this could be diffuse,
photoionized material that is still in the system, but not part of the
main accretion flow, and truly moving with low velocity.

The S-wave seen in the O\textsc{v} \\lambda 1371 trailed spectra can be
associated with the strong emission site close to the stream-disk
interaction region. The He\n\textsc{ii} \\lambda 1640 line produces good results
despite being far from the strongest line. The emission is spread
out in a ring consistent with emission from a disk. Emission ap-
pears to extend along the stream in a similar way to the optical
He line maps. Here, however, this emission region is signifi-
cantly extended around the rim of the disk. The center of this
emission region is close to that in the O\textsc{v} \\lambda 1371 map. A similar
emission region is apparent in the N\textsc{v} \\lambda 1240 tomogram.
The other UV maps show high points of emission at a variety of
positions.

All of the ultraviolet maps from the \textit{HST} data set show a ring
of emission consistent with a disk. A possible exception is O\textsc{v}
\\lambda 1371, which appears to lack emission in the orbital phase range
$\phi = 0.1-0.5$. This may just be a relative deficit compared to the

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**Fig. 8.**—Tomograms formed from the CTIO and VLT data. The expected track of material leaving the L1 point and traveling ballistically is marked by a solid line. The
Keplerian velocity at each point along that track is plotted as a dot-dashed line. The secondary's Roche lobe, the velocity of the primary, and the Keplerian velocities at the
expected position of the edge of the disk and at the circularization radius are also plotted. The circle in the bottom right of each panel has a diameter equal to the velocity
resolution of the data. [See the electronic edition of the Journal for a color version of this figure.]
strong emission region. The N $\lambda 1240$ line suffers from the interference of the Ly$\alpha$ adjacent absorption, which is difficult to remove with great confidence. The more isolated C $\lambda 1549$ would seem a better bet for a good result, but unfortunately the line consists of two components separated by the equivalent $\sim 500$ km s$^{-1}$. Convolved with the double-peaked disk profile this leaves a difficult data set to disentangle and gives rise to the filling in of emission at low velocity. The C $\lambda 1176$, O $\lambda 1371$, and Si iv $\lambda 1394$, 1403 lines are all weaker, with the latter also sharing the complication of being a doublet. While the reconstruction routine does allow such doublet lines to be specified with their relative strengths there is inevitably a loss of information in such an entangled case.

The high points of emission in the C $\lambda 1176$ map all occur along the projected ballistic stream deep into the disk. The line is extremely weak and so potentially unreliable, however.

The high-excitation line Si iv $\lambda 1400$, C iv $\lambda 1549$, N $\lambda 1240$, and O $\lambda 1371$ tomograms all show emission in the phase range $\phi \sim 0.65–0.75$. The latter two lines, with higher, but almost equal, ionization potentials, appear to come from further into the disk. None of this emission lies along the continuation of the ballistic stream or the Keplerian velocity corresponding to the stream position as envisioned by the overflowing stream model. However, it is consistent with the region downstream of the hot spot impact and/or the early part of a stream overflow.

The Si iv $\lambda 1400$ tomogram is similar to that from He ii $\lambda 1640$. Strong emission sites are scattered around the disk rim although no emission appears along the stream.

Given the velocity resolution of the data, it is difficult to say with certainty whether the strong emission sites in the tomograms occur at velocities significantly different from that expected at the disk rim. The most reliable maps in this regard would be those from the first VLT data set for He ii $\lambda 5412$ and He ii $\lambda 4686$. In these maps, there is emission in the stream region.

The former also shows emissions sites close to the circularization velocity. These maps, along with the emission site interior to the disk shown by C $\lambda 1176$, N $\lambda 1240$, O $\lambda 1371$, and Si iv $\lambda 1400$ all hint that the stream may be overflowing the disk.

We might, alternatively, attempt to explain the velocity of the emission being in an area we would associate with disk material in terms of a thick rim model. If the disk were puffed up by X-ray irradiation, it would be natural to expect high-ionization lines to appear near the rim. However, contemporaneous X-ray observations in Paper III show dips at a wide range of phases. Indeed, similar to the results of Bonnet-Bidaud et al. (2001), only the ranges $\phi = 0.2–0.3$ and $\phi = 0.45–0.55$ show a lack of dipping activity. Given azimuthal disk symmetry (or some close approximation) why would one particular phase be singled out for emission? In the overflowing stream model, this can be attributed to the different physical conditions that exist along the stream and in each region of the disk with which it interacts with increasing ionization as the central star is approached.

3.4.1. Constraining the Mass Ratio $q$

We can compare the same Doppler tomograms with tracks generated using different choices for the $q, i$ pairs allowed by the observed eclipses. This is useful as it is often possible to constrain further the acceptable range of $q$ (and hence $i$) to those consistent with identifiable features, in particular the stream. We would expect the stream emission to arise at velocities between the ballistic and Keplerian value along the stream trajectory. The tomogram formed from the VLT1 observations of the He ii $\lambda 4686$ line are shown in Figure 10 with markings generated for a selection of $M_i$ values. For $M_i = 1.35\, M_\odot$, these appear to favor values of $M_2$ at the high end of the range considered in Paper I and the observations are most compatible with the assumption of a main-sequence secondary ($M_2 = 0.46\, M_\odot, i = 75.5$, model 3). Özel (2006) recently proposed a lower limit $M_i > 2.1\, M_\odot$. 

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**Fig. 9.** Tomograms formed from the HST data. Again a circle has been plotted in each panel with a diameter equal to the velocity resolution of the data. [See the electronic edition of the Journal for a color version of this figure.]
However, in that case the model 3 ballistic trajectory barely passes through the strong emission region. To achieve the same degree of agreement as for $M_1 = 1.35 M_\odot$, we would require $M_2 \approx 0.84 M_\odot$ (plotted as model 4), approximately 80% more massive than a main-sequence companion. Schenker & King (2002) showed how an overmassive secondary can arise as the result of mass transfer stripping away the secondary's envelope to reveal a helium rich core. However, the example they give only has a maximum mass excess of around 40% and then only for $M_2 < 0.1 M_\odot$, significantly smaller in both parameters than we would require. These difficulties led us to retain the assumption of a main-sequence secondary with $1.35 M_\odot$ primary as the choice for the markings in Figures 8 and 9 above.

4. CONCLUSIONS

Stepping back from the details, we can attempt to identify the common features present in the data set, focusing on the highest quality lines. Beginning with the tomograms, these appear to show two components across several lines. First, a ring of emission is present that can likely be associated with the accretion disk (or a coronal layer above it). Second, excess emission is usually present on the left-hand side of the tomogram. In He II $\lambda$4686, this is in the top left quadrant and consistent with the accretion stream and/or impact point, with the implied disk radius consistent with tidal truncation. In the higher ionization resonance lines, most obviously O v and N v, this is preferentially lower in the tomogram, below the ballistic stream. This suggests emission from material carried downstream in the disk from the initial stream-impact. He II $\lambda$1640 appears as a hybrid of the two extremes. The velocities of the high-excitation lines are lower than expected from a purely ballistic stream overflow, but appear higher than expected from material at the disk rim; they are intermediate between Keplerian velocities at the disk rim and the circularization radius, suggesting that some penetration of the disk is occurring. Light curves provide support for this trend. He II $\lambda$4686, which appears to originate at the stream-impact point in the tomograms, is deeply eclipsed as expected, whereas the UV lines including He II $\lambda$1640, which appear to originate from downstream of the stream-impact point, show no eclipses. Comparison of the stream position in the Doppler tomograms to models supports the hypothesis that the secondary is a main-sequence star and the system has a mass ratio of 0.34.

Examining the trailed spectra, the O v line provides the clearest S-wave component, and appears to show least disk emission. Its S-wave can be identified in the trailed spectra of other lines, particularly when one allows for their multiplet structure where appropriate. Most surprising is that the same S-wave appears to trace out absorption in the Balmer lines. While it is not required that gas with the same velocity be co-spatial, if it is, this points to a two-phase medium. Cool material will produce low-ionization absorption lines when backlit by hotter underlying material, whereas the hot component will produce high-ionization emission lines, as observed. The presence of this component in He i at high velocities at both phases 0.0 and 0.5 in the VLT2 trailed spectrum indicates that absorption cannot simply be by the disk rim but must be by material above the disk, as the rim will not be backlit at $\phi = 0.5$.

The picture that thus emerges is that the accretion stream impacts the disk and some material overflows or penetrates it, albeit with velocities closer to the disk rim than to a purely ballistic overflow. The overflowing material forms a two-phase medium. The densest clumps remain relatively cool and produce low-ionization absorption of the brighter background disk, whereas the lower density material is hotter and produces high-ionization emission.

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