RW Aur A FROM THE X-WIND POINT OF VIEW: GENERAL FEATURES

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ABSTRACT

In this paper, the RW Aur A microjet is studied from the point of view of X-wind models. The archived Hubble Space Telescope/STIS spectra of the optical forbidden lines [O i], [S ii], and [N ii] from RW Aur A, taken in Cycle 8 with seven parallel slits along the jet axis, spaced at 0′07 apart, were analyzed. Images, position–velocity diagrams, and line ratios among the species were constructed, and compared with synthetic observations generated by selected solutions of the X-wind. Prominent features arising in a steady-state X-wind could be identified within the convolved images and position–velocity diagrams, including FWHM and high-velocity peaks on both of the redshifted and blueshifted jets. The well-known asymmetric velocity profiles of the opposite jets were built into the selected models. We discuss model selections within the existing uncertainties of the stellar parameters and inclination angle of the system. In this framework, the mass-loss rates that were inferred to be decreasing along the jet axis in the literature are the results of slowly decreasing excitation conditions and electron density profiles. Despite the apparent asymmetry in the terminal velocities, line intensities and mass-loss rates, the average linear momenta from the opposite sides of the jet are actually balanced. These previously hard-to-explain features of the asymmetric RW Aur A jet system can now be interpreted in a different but self-consistent manner within the X-wind framework.

Key words: ISM: jets and outflows – ISM: kinematics and dynamics – stars: individual (RW Aur A) – stars: mass-loss – stars: pre-main sequence – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

The RW Aur system is one of the brightest (V ≈ 10.51; Kenyon & Hartmann 1995) and most studied members of the Taurus-Auriga star forming region (at a distance of 140 pc; Kenyon et al. 1994). It is a wide binary system with a separation of ≈ 1″40 (White & Ghez 2001). Both members possess circumstellar disks that are tidally interacting with each other (Cabrit et al. 2006). The primary, RW Aur A, is the only source that drives a bipolar jet. The jet was first inferred from its optical forbidden line profiles (Hamann1994; Hartigan et al. 1995) and later confirmed by narrow-band imaging (HH 229; Mundt & Eislöffel 1998). RW Aur A is known to be actively accreting with an accretion rate of 0.5–1.6 × 10−6 M⊙ yr−1 inferred from optical veiling (e.g., Hartigan et al. 1995; White & Hillenbrand 2004).

Overall, the RW Aur A jet has a strikingly well-collimated appearance (e.g., Mundt & Eislöffel 1998; Dougados et al. 2000; Woitas et al. 2002). The [S ii] λλ6716 + 6731 image of Mundt & Eislöffel (1998) showed that the blueshifted jet lies exactly along the position angle of 130° at least up to 110°. The jet is marginally resolved within 56 AU using Canada–France–Hawaii Telescope (CFHT) adaptive optics and Hubble Space Telescope (HST)/STIS. The widths of the jet slowly increase beyond this distance with an opening angle of 3°–4° (Dougados et al. 2000; Woitas et al. 2002), and they appear to expand more rapidly closer to the source (within 0.5″) than they do farther away. Such jet width trends have been difficult to interpret in the past (Reipurth & Bally 2001), as the observed widths were often interpreted to be the extent of the bow shock wings and the true jet could be much narrower. Farther than 0.5″ from the sources, the widths of the RW Aur A jet become wider as the intensity decreases along the jet axis, which was also observed by HST for HH 34 (Ray et al. 1996). The fluxes of both blueshifted and redshifted jets decrease by an order of magnitude from 0.5″ to within 2″ from the star. Woitas et al. (2002) considered the measured widths to be marginally consistent with an X-wind jet in Shang et al. (2002) and the self-similar disk wind model in Garcia et al. (2001) at high accretion efficiencies. Kinematics based on long-slit spectroscopy makes the RW Aur A jet a textbook example of a microjet. The position–velocity (PV) diagrams of its brightest forbidden lines, such as [S ii], [O i], and [N ii], clearly display a single intensity peak at each position along the jet axis. The centroid velocity lies around 100 km s−1, which is identified as the high-velocity gas tracing the collimated jet. The velocity widths are broad close to the source and narrow toward its terminal velocities, far along the length of the jet (e.g., Bacciotti et al. 1996; Hirth et al. 1997; Pyo et al. 2006; Melnikov et al. 2009; Hartigan & Hillenbrand 2009). The low-velocity intensity peaks around 5–20 km s−1 (Hirth et al. 1997), which are usually present in many classical T Tauri stars, are virtually non-existent either in the optical HST/STIS data (Woitas et al. 2002; Melnikov et al. 2009; and this work) or in the near-infrared [Fe ii] λ1.644 μm spectra from Subaru/IRCS (Pyo et al. 2006) and Keck/NIRSPEC (Hartigan & Hillenbrand 2009). Although Hartigan et al. (1995) and Alencar et al. (2005) reported detections of some low-velocity peaks in [O i] λ6300, these peaks were highly variable and have been discarded as being simply transient (on a timescale of months). The strong collimated emission at high velocity makes the RW Aur A jet an ideal candidate to examine using models with magnetocentrifugally driven winds that arise from a narrow region close to the inner edge of the disks, for example, those that may resemble X-winds (Shang et al. 1998, 2007; Shu et al. 2000). In fact, it is our primary goal to compare this set of data with the best fits generated by models based on

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the X-wind solutions using the approaches outlined in Shang et al. (2002).

Despite the predominant high-velocity emission, the asymmetry across the opposite sides of the RW Aur A jet has long been documented in the literature (Hirth et al. 1994, 1997; Bacciotti et al. 1996; Woitas et al. 2002; López-Martín et al. 2003; Pyo et al. 2006; Melnikov et al. 2009; Hartigan & Hillenbrand 2009). The level of asymmetry in RW Aur A is among the largest in the eight asymmetric T Tauri jets reported in Hirth et al. (1994), who excluded interpretations based on different spatial orientations on opposite sides of the source, uncorrelated time variabilities, different degrees of deceleration, or different degrees of collimation. Instead, they concluded that such strong asymmetry should arise in the acceleration process of the jet itself. Woitas et al. (2002) derived a velocity ratio of 1.6–1.75 within 0'.5 from the source with HST/STIS, and attributed the origin of the asymmetry to the “central engine.” López-Martín et al. (2003) measured the proper motions of knots and found that they have the same ratios as their radial velocities, and that the velocity asymmetry should be intrinsic to the jet. The ratios of proper motion are well maintained up to 4'.6 and 1'.6 from the source, along the blueshifted and redshifted jets, respectively (McGroarty et al. 2007). We will treat the velocity asymmetry as an intrinsic property built into our models to explain the overall phenomena.

The asymmetry exists not only in the flow velocities but also in the line intensities and the physical conditions derived from the line ratios. Mundt & Eisloeffel (1998) noted that the two opposite sides of the jet differ significantly in their spatial extent, with the [S II] jet extending to ∼106′′ and ∼50′′ on the blueshifted and redshifted sides, respectively. The red jet is brighter in the inner ∼10″ (Bacciotti et al. 1996), and remains so down to 0′′.2 from the source, as seen in both the optical (Melnikov et al. 2009) and near-infrared (Hartigan & Hillenbrand 2009). Hirth et al. (1997) noted that at ∼1" angular resolution, the red jet has a larger electron density, a higher [S II] λ6331/λ6300 ratio, and a lower Hα/λ6364 ratio than the blue jet. On the other hand, the faintness of the blue jet prevented Bacciotti et al. (1996) from attempting a reliable diagnostic analysis using ground-based spectra, which led Woitas et al. (2002) to assume similar [N II] λ6583/λ6560 and [S II] λ6364/λ6300 ratios for both sides of the jet for the HST/STIS spectra in their later analysis. Melnikov et al. (2009) re-examined the same STIS data set and obtained a smaller [N II] λλ6548 + 6583/λ6560 + 6363 ratio but a larger [S II] λλ6716 + 6731/λ6300 ratio in the red jet, which implies a lower ionization fraction and temperature than the blue jet. We will re-examine the data set, and analyze the line ratios and physical conditions based on the diagnostic approach developed in Shang et al. (2002) for the X-wind jets.

As a result, the fundamental physical properties of the RW Aur A system may appear to be asymmetric. Mass-loss and momentum rates will be asymmetric when they are inferred from the measured asymmetric radial velocities, jet widths, and the electron densities obtained from the line ratios (Woitas et al. 2002; Melnikov et al. 2009). Woitas et al. (2002) reported that if similar physical conditions had been adopted, the red jet would carry one-half of the mass-loss rate and one-third of the momentum rate carried in the blue jet. The imbalance of momentum may cause dynamical effects such as recoil. Woitas et al. (2002) calculated an upper bound of 8 km s⁻¹ for the recoil, under the assumption that the imbalance persisted during the entire pre-main-sequence lifetime of the star. They stated that this recoil value is probably a gross overestimate because it is possible that earlier accretion of mass onto the star might have been more symmetric, or that linear momentum balance might have been maintained over time. The dynamical time of these jets (∼10⁵ yr or less) is relatively short, diminishing the reasons one might expect a persistent imbalance during the entire pre-main-sequence phase (about 10⁶ yr). Melnikov et al. (2009) revised the calculation by independently deriving the electron densities and ionization fractions from each side, and derived similar mass-loss rates for the two sides. They attributed the asymmetry to inhomogeneous ambient material or to the magnetic configurations. Both works, Woitas et al. (2002) and Melnikov et al. (2009), leave the momentum unbalanced in the presence of the observed velocity asymmetry. In this paper, we will undertake similar analyses based on the same HST/STIS data set used in previous works, and demonstrate that the basic jet properties should be balanced in spite of asymmetries observed in velocity and mass loss.

The X-wind framework provides an attractive possibility for confronting models with high angular-resolution observations. Through star–disk interaction, the stellar magnetic fields can truncate the disk at the corotation radius in steady state, where the field is trapped and pinched toward a small area called the X-region at the inner edge of the disk. The material from the disk can accrete onto the star via a funnel flow along the field lines connecting the inner disk edge and the star. Meanwhile, the excess angular momentum from the star can be transported to the X-region and material can be magnetocentrifugally ejected along the open field lines as the X-wind. Streamlines of the wind flow fan out from the X-region, and gradually collimate along the axis of rotation. Shang et al. (1998) demonstrated the kinematic features of an X-wind through synthetic spectra with broad line widths close to the base of the jet, which then narrow to the profile of a single-velocity component upon approaching the flow’s terminal speed. Shang et al. (2002) self-consistently calculated the ionization and thermal conditions for the semi-analytic X-wind solutions and demonstrated how the excitation conditions can influence the synthetic images as “optical illusions,” finding a good match of line ratios from available Herbig–Haro objects and microjets. Based on the work by Shang et al. (1998, 2002), here we attempt a comparison of the X-wind models with those well-known features of the RW Aur A jet.

In this paper, we demonstrate a step-by-step comparison of the high-angular-resolution data with theoretical models generated within the X-wind solutions through the analysis of key observed features. RW Aur A is an excellent candidate for such purposes due to its one characteristic high-velocity feature that simplifies the modeling. In Section 2 the analysis of HST/STIS archival data is addressed and our parallel procedures for producing synthetic observable quantities from the models are presented. The observed properties of the jet extracted from the data, i.e., images, PV diagrams, and the line ratios are discussed in Section 3.1. An illustrative fit to the RW Aur A jet is given in Section 3.2 and directly compared with the observational data. Finally, the interpretation of these unusual features of RW Aur A is discussed in the theoretical framework based on the X-winds in Section 4.

2. METHODS

2.1. Archival HST/STIS Data

We obtained HST/STIS spectra of RW Aur A from the Multi- mission Archive at Space Telescope (MAST). The spectra were
taken on 2000 December 10 and have been previously reported by Woitas et al. (2002, 2005) and Melnikov et al. (2009). In this set of data, a 52″ × 0′.1 slit was used with the STIS G750M grating. The slit was displaced in steps of 0′.07 parallel to the jet axis at seven different positions, creating a total field of view of about 0′.5 across the jet. Each exposure produced a two-dimensional spectral image of 52″ long in the spatial axis and 6295–6867 Å in the dispersion axis, covering the seven brightest emission lines: [O i] λ6300, 6363, [N ii] λ6548, 6583, [S ii] λλ6716, 6731, and Hα. The slit sampled the emission at a nominal rate of 0′.05 pixel−1 with an angular resolution of ∼0′.1 (FWHM), and a spectral sampling rate of 0.554 Å pixel−1 with a 2.5 pixel line width, corresponding to ∼25 km s−1 pixel−1 and a FWHM ∼65 km s−1 at ∼6500 Å.

The pipeline-processed spectra taken directly from MAST work reasonably well for our purposes. Hot pixels were present at specific positions on the CCD, but they fall primarily on line-free regions. Further reductions were performed to remove the baseline undulations caused by wavelength rectification of the undersampled stellar continuum and the contribution from the reflection nebula. Each of the seven spectral images was first divided into three sub-images containing lines of [O i], Hα+[N ii], and [S ii], respectively. On each sub-image, we examined the rows containing the redshifted jet extending up to 4″ from the star and the blueshifted jet extending up to 2″ from the star. For each row, we fit the baseline with a Legendre polynomial, up to the 10th order, with IRAF/STSDAS3 G750M and downhill simplex χ² minimization.

PV diagrams were obtained for each line and each slit, relative to the systemic velocity of +16.0 km s−1 (Woitas et al. 2002). [O i] λ6300 emission from the blueshifted jet with velocity higher than −235 km s−1 was cut off due to the wavelength coverage of the G750M grating. Line profiles were also extracted from the PV diagrams every 0′.05. Each profile was fitted with a single Gaussian and a linear baseline in IRAF/STSDAS G750M with recursive χ² minimization. In the intensity maps, as constructed in Woitas et al. (2002), a single Gaussian was fitted to the transverse profiles every 0′.05 using the Levenberg–Marquardt method for the amplitudes, intensity centroids, and FWHM. For each pixel of the two-dimensional STIS stack, the ratios between the pairs of lines were used to construct line-ratio diagrams for [S ii] λλ6716/6731, [N ii] λ6548/ [O i] λ6300, and [S ii] λ6731/[O i] λ6300. The data points were further arranged according to their spatial distribution.

In the following analysis performed on the model data cubes, operations and conditions applied in the observational analysis were adapted so that the model data set can be properly compared with the observed data set.

2.2. Synthetic Maps

Synthetic images and long-slit spectra are calculated for various X-wind configurations using the methods and examples illustrated in Shang et al. (1998, henceforth SSG) and Shang et al. (2002, henceforth SGS). We follow the approach adopted in SGS to obtain a self-consistent thermal structure for each model, in which various ionization and recombination and heating and cooling processes associated with the wind are considered. These include hydrogen photoionization and H− photodetachment by photons from the star and accretion hot spots, X-ray heating and ionization, collisional ionization, ambipolar diffusion heating, and external heating arising from mechanical origins in the flows. In a magnetized star–disk system, the closed stellar magnetic loops confine plasma of the soft X-ray temperature, and the sites of magnetic field line reversals between the star and the wind are prone to reconnection events that can generate harder X-rays (see, e.g., Figure 1 of Shu et al. 1997). SGS concluded that X-rays are effective at ionizing the base of the X-wind (see also Shang et al. 2010, henceforth SGLL), and that mechanical heating can easily heat the flow to 8000–10,000 K when a small amount of mechanical energy is converted to heat. In this work, we adopt the conventions defined in SSG and SGLL, and find solutions normalized by stellar parameters for the RW Aur A system.

We extend the reaction network to include the ionization balance of oxygen, sulfur, and nitrogen. The charge exchange with the H atom controls the equilibria between O0 and O+, and N0 and N+. Because they have similar ionization potentials (13.60, 13.61, and 14.53 eV for H, O, and N, respectively), sulfur is assumed to be singly ionized as a result of its lower ionization potential (10.36 eV). Atomic data from Mendoza (1983) were used in these calculations, and updated collisional strengths of [S ii] (Cai & Pradhan 1993) were adopted.

To obtain an optimal fitting with the observed spectra, the mass-loss rate Ṁw defined in Shu et al. (1994a), X-ray luminosity LX (Equation (3.10) in SGLL), and the coefficient of heating αX (Equation (5.2) in SGLL) were adjusted to obtain proper thermal profiles for emission. The fiducial cases shown in SGLL and Shang et al. (2004, henceforth SLGS) were taken as initial model standards. The initial values of Ṁw and LX were first allowed to vary with the fixed ratio LX/Ṁw = 3 × 10¹³ erg g⁻¹, a measure of X-ray attenuation previously used in SGSL and SGLL. The values of αX are adjusted to produce thermal profiles that generate emission fluxes matching the observed ones. The properties of the synthetic images and spectra are derived for further analysis and comparisons with the STIS data. We note that the actual stellar system’s emission always looks knottier than that of the synthetic profiles produced by the steady-state models, and that the level of the X-rays adopted in our models in this paper is on the higher end of the flares attained by low-mass pre-main-sequence stars (e.g., Getman et al. 2008; McClure & Wolk 2011). As explained in SGLL, the higher level of X-ray luminosity adopted in our modeling scheme may reflect the fact that these X-rays may have experienced higher extinction near the base of the wind before they could come out and reach the level of ionization obtainable for an otherwise lighter wind. A lower X-ray luminosity can be adopted instead if the X-rays are generated at a more elevated position relative to where the ionization actually takes place. This can effectively lower the absorption column in the context of the X-wind models (H. Shang et al., in preparation). By adopting and keeping the fixed ratio LX/Ṁw = 3 × 10¹³ erg g⁻¹, the analysis shown in this work is consistent and can easily be compared with past works using this approach (SGSL, SLGS, and SGLL). We define and focus on the overall trends and profiles rather than local variations within individual knots in the process of fitting and model–data comparisons.

The synthetic images have to be generated at very high resolution using high sampling rates for convolution. The maps were convolved with the telescope point-spread function (PSF) while retaining spatial sampling in the original map. STIS

3 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation; STSDAS is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.
in instrumental profiles were applied to the long-slit spectra. Each of the profiles was convolved with a two-dimensional Gaussian of 0.1 × 65 km s−1 FWHM, and resampled at 0.05 and 25 km s−1, based on profiles of the STIS 52′′ × 0.1 slit and G750M grating. The resulting PV diagrams were fitted using a one-dimensional Gaussian at each spatial point sampled using the downhill simplex method. The fitted values of the line intensities, velocity centroids, and velocity widths were compared with those derived from the observed spectra along the jet axis. A distance of 140 pc to the RW Aur A system was adopted to match the physical scales between the observed and synthetic maps.

The synthetic line ratios of [S ii] λ6716/6731, [S ii] λ6731/[O i] λ6300, and [N ii] λ6583/[O i] λ6300 were calculated from different positions in the integrated line intensity maps.

2.3. Properties of the RW Aur A System

Properties of the RW Aur A system affect the actual model fits to the observations because the stellar parameters determine the actual dimensional values of the models. The systematic velocity also affects the values of the observed jet speeds relative to the driving source and the velocity ratios. Furthermore, the inclination angle may introduce uncertainties to the terminal velocities. The stellar parameters in the literature, determined from various evolutionary tracks, veiling rJ and visual extinction AV, stellar mass M∗, stellar radii R∗, spectral lines, and luminosity, are summarized in Table 1 (Hartigan et al. 1995; Stout-Batalha et al. 2000; Woitas et al. 2001; White & Ghez 2001). It can be seen that the ranges of inferred stellar masses, radii, and luminosities have not varied by more than a factor of two. Within the uncertainties, we adopt a reference value of M∗ = 1 M⊙ and R∗ = 2 R⊙ for illustrative purposes throughout this work.

RW Aur A may have a varying heliocentric radial velocity. For the same STIS data set, Woitas et al. (2002) adopted a value of +16.0 km s−1 (Petrov et al. 2001) and obtained an average velocity ratio for the jet components of ~1.6. On the other hand, Melnikov et al. (2009) adopted +23.5 km s−1 (Woitas et al. 2005) and obtained a higher value of the ratio ~1.8. The value obtained by Woitas et al. (2005) was based on a single fitting to the Li i λ6708 absorption in the current HST/STIS data set, which we re-analyze with a value of +22.1 ± 0.61 km s−1. For illustrative purposes, we adopt the averaged value of +16.0 km s−1 (Petrov et al. 2001; White & Hillenbrand 2004) and set the nominal velocity ratio to be 1.6 throughout this work. The radial velocities reported in the literature and their inferred jet velocity ratios are summarized in Table 2.

Various groups have attempted to derive the inclination angle of the RW Aur A system. Woitas et al. (2002) compared the proper motions of the RW Aur redshifted jet between CFHT/PUEO (1998) and HST/STIS (2000) observations and derived a value of 53° ± 5°. López-Martín et al. (2003) inferred the value to be 46° for both jets with corrected PUEO pixel size. Alencar et al. (2005) modeled the emission and absorption profiles of the Balmer lines and Na D lines with the disk-wind model of Blandford & Payne (1982) and inferred a range between 55° and 65°. Cabrit et al. (2006) modeled the 12CO (J = 2–1) spectra of the disk around RW Aur A with Keplerian disk profiles following Beckwith & Sargent (1993), and found that the line profiles can be matched with 45° or 60°. The range of inclination angles agrees reasonably well within 45° and 60°, which we will take as the uncertainty introduced when one de-project velocities.

Within the range of stellar parameters, we explore combinations of the wind mass-loss rateṀw, disk truncation radius Rd (the X-point; see Shu et al. 1994a), and solutions of the X-wind models (Shu et al. 1994a, 1994b, 1995; Shu & Shang 1997; Shang 1998; Shang et al. 1998, 2002, 2004, 2010 [SSG, SGSL, SLGS, SGLL]; Cai et al. 2008). Details of the magnetic configurations and their observational properties will be presented in a separate publication. In this work, we focus on specific features that one can derive from the observed properties of the RW Aur A jet, which are applied as selection criteria for the models. The X-winds that satisfy the identified constraints are further analyzed and compared with the STIS data set.
The velocity asymmetry, if intrinsic to the system, reveals an interesting connection between winds launched from the opposite sides of the disk in the X-wind context. In a steady state, the inner disk truncation radius coincides with the X-point, and opposite sides of the disk in the X-wind context. In a steady state, winds above and below the disk from the X-point. The equivalent individual mass-loss rates that enter into either hemisphere are half of the inferred model values. The individual mass-loss rates for each hemisphere are reported in Sections 3 and 4.

3. RESULTS

In this section, an example is given to demonstrate the general principles in applying the X-wind models to observations. We first show the observed features of the RW Aur A jet extracted from the archival HST/STIS data.

3.1. Observed Features

The two sides of the RW Aur A jet are asymmetric in appearance. The narrow-band images of three forbidden lines $[\text{S} \text{II}] \lambda$6731, $[\text{N} \text{II}] \lambda$6583, and $[\text{O} \text{I}] \lambda$6300 for the red jet and $[\text{O} \text{I}] \lambda$6300 for the blue jet) are shown in gray scale in Figure 1. Both the blue and the red jets are knotty, and the knots become fainter as the jet propagates outward. The innermost knots appear to be tightly connected, while the outer knots have traveled farther apart. The red jet extends beyond 4′ and at least four knots can be identified. The blue jet is overall dimmer by factors of three to four, and extends up to 2′ with three knots identified. The extent of the asymmetry slightly differs among line species. $[\text{N} \text{II}]$ is overall dimmer and shows less asymmetry than $[\text{O} \text{I}]$ and $[\text{S} \text{II}]$, and lacks emission beyond R4. The red jet appears somewhat more compact in the transverse direction than the blue jet.

The asymmetry in the intensities and velocity centroids are indeed pronounced features on the PV diagrams. The velocity ratios between the blue and red jets are ~1.56 to 1.60, which can be traced to the innermost detectable region of the system at 0.2. Figure 2 shows the PV diagrams of $[\text{O} \text{I}] \lambda$6300 for the red jet and $[\text{S} \text{II}] \lambda$6363 for the blue jet), $[\text{N} \text{II}] \lambda$6583, and $[\text{S} \text{II}] \lambda$6731 extracted from the central slit. The velocity ranges from $-25$ to $+300 \text{ km s}^{-1}$ in the red, and from $-350$ to $+25 \text{ km s}^{-1}$ in the blue. The knots were identified by the peak positions in the PV diagrams and are labeled as such in Figure 1. The line shapes of the knots can be fitted with a single Gaussian profile throughout the jet, clearly showing that the jet is dominated by a single velocity component. The velocities at the centroids range...
Figure 1. Narrow-band images of the RW Aur A jet extracted from the HST/STIS archived data. The jet axis is plotted as the abscissa, with the distance increasing along the position angle of 130°. The ordinate is the distance across the jet obtained with seven slits separated by 0′′07. The surface brightness of the lines are shown on logarithmic scale between $5 \times 10^{-16}$ and $5 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$. In each panel, the knots are identified and labeled as in López-Martín et al. (2003), and we label the "stationary knot" on each side of the jet in parentheses.

(A color version of this figure is available in the online journal.)

Loci of the line ratios from the blue and red jets do not overlap on the cross-ratio plots. The line ratios between [N II] $\lambda 6583$/[O I] $\lambda 6300$ and [S II] $\lambda\lambda 6716/6731$/[O I] $\lambda 6300$, and between [S II] $\lambda\lambda 6716/6731$ and [S II] $\lambda\lambda 6731$/[O I] $\lambda 6300$ are shown in Figure 3. We show the line-ratio plots for points within 0′′95 (B4 + B5) from the source for the blue jet, and within 0′′65 (R7) for the red jet, at a distance ratio approximately proportional to their respective velocities. The line ratios integrated over the slits labeled by their positions from the source are shown in the left panels, and those from the individual slits are shown in the right panels. Only those points with relative uncertainties lower than 50% are shown. We focus the analysis on data points from the three central slits since the outer slits do not contribute statistically significant information, as can be seen in the right panel of Figure 3. The line ratios roughly increase with distance along the jet axis. The line ratios derived from different slits do not segregate into distinct groups, but rather they scatter around a general trend. The emissions appear to come from continuous media of similar physical conditions within each side of the jet, but each component shows its own distinct trends. In the red jet, the $[\text{S II}] \lambda\lambda 6716/6731$ ratio clusters around similar values of 0.45–0.63, whereas the $[\text{S II}] \lambda 6731$/[O I] $\lambda 6300$ ratio ranges from 0.3 to 1.0. It also shows an increasing trend with increasing values of $[\text{S II}] \lambda\lambda 6716/6731$/[O I] $\lambda 6300$ from the outer slits. In the blue jet, both the ratios of the $[\text{S II}]$ doublets and $[\text{S II}] \lambda 6731$ to [O I] $\lambda 6300$ have large scatters due to the weakness of the lines, and there is no clear correlation of the values. Similar trends exist for the $[\text{N II}] \lambda 6583$/[O I] $\lambda 6300$ ratio: those in the blue jet span a wider range, while those in the red jet are located within a confined region; however, the two line ratios $[\text{S II}] \lambda 6731$/[O I] $\lambda 6300$ and $[\text{N II}] \lambda 6583$/[O I] $\lambda 6300$ are clearly positively
correlated, from the central to the outer slits. Perhaps due to the faster drop-off of the [O i] signal in the blue jet in particular, points from a farther distance tend to drift and pile upward near the upper right corner of the [N ii] λ6583/[O i] λ6300 to [S ii] λ6731/[O i] λ6300 panels with even larger scatter. Those points were not displayed in Figure 3 for clarity of presentation.

3.2. Sample Fit for the RW Aur A System

In this subsection, a sample fit for the RW Aur A jet is shown. For simplicity, we demonstrate one case that overall could capture the major features of the jet in this paper. Other solutions are possible, within the observational constraints set by the HST/STIS data, such as those listed in Table 4.

The sample is described by properties outlined in Section 2.3 for RW Aur A: stellar parameters \((M_*, R_*) = (1 M_\odot, 2 R_\odot)\), a systemic velocity of +16.0 km s\(^{-1}\), an inclination angle of 55°, and a disk truncation radius \(R_x = 0.12\) AU (see Table 3 for the range of possible choices). With these parameters, one solution gives an average projected velocity of −170 km s\(^{-1}\) for the blue side and the other gives +115 km s\(^{-1}\) for the red side, as inferred from the archival data. The velocity coverage is in the range of 200–310 km s\(^{-1}\) for the blue, and 120–200 km s\(^{-1}\) for the red. They possess the properties of those pointed out by SSG, such as the cylindrically stratified density structures, broad line profiles near the bases, and slowly collimating streamlines toward the axis over a large distance. The density contours and streamlines and the PV diagrams are similar to Figures 1 and 3 of SSG, respectively.

We follow SGSL in finding the optimal parameters for mass-loss rates \(\dot{M}_w\), X-ray luminosities \(L_X\), and mechanical heating coefficient \(\alpha_h\). During the parameter searches, the ratio of X-ray luminosity to mass-loss rate, \(L_X/\dot{M}_w\), is set to be \(3 \times 10^{13}\) erg g\(^{-1}\), as in SGSL, SLGS, and SGLL. From parameters adopted in the fiducial case of SGSL for both winds in the blue and red hemispheres, \(\dot{M}_w, L_X,\) and \(\alpha_h\) are individually varied on each side to find the optimal matches for the intensity profiles and line ratios. The optimal sets of parameters are given in Table 5, which capture the overall features reasonably well. Although the emission is knotty and the profiles and velocities have variations and scatter, clear average trends can...
be clearly identified for individual lines along the jet axis. For the individual mass-loss rates of $3 \times 10^{-8} \, M_\odot \, \text{yr}^{-1}$ in blue and $5 \times 10^{-8} \, M_\odot \, \text{yr}^{-1}$ in red, and $\alpha_h = 0.0010$ for the blue and $\alpha_h = 0.0015$ for the red, the physical properties and emission profiles are illustrated in Figures 4–9.

The physical scale in Figures 4 and 5 covers the transverse and longitudinal dimensions of the seven slits: 50 AU in horizontal distance $\sigma$ and 150 AU in length $z$ along the jet axis, as $1''$ corresponds to $\sim 140$ AU for RW Aur A. Figure 4 shows the velocity contours on top of the electron density profiles and Figure 5 shows the distributions of the electron fraction and temperature. In Figure 4, the electron density is also cylindrically stratified due to the underlying density as described in SSG, from within 50 AU out to larger distances. Near the base of the jet, it casts an opening with a conic shape in the images, as pointed out in SSG. The velocity increases toward the axes on both sides of the jet, where the flows are denser and faster, until it reaches the terminal velocities (Shu et al. 1995; SSG). In Figure 5, the electron fraction and temperature follow similar behaviors to those in SSG. Both $x_e$ and $T$ increase toward the inner boundaries of the wind, and peak within 5 AU from the launch point. The blue jet has a higher level of electron fraction and temperature than the red jet, supporting the trends observed from the line-ratio diagnosis diagrams.

We show comparisons in the PV diagrams, intensity profiles, image FWHM, and velocity centroids for [O i] $\lambda\lambda 6300, 6363$ and [N ii] $\lambda\lambda 6583, 6548$ in Figures 6–8. On the left, the profiles of intensity peaks and their FWHM along the jet are shown for the inner 2.5'' from the source. On the right, the contours of the synthetic emission spectra (red for the red jet, and blue for the blue jet), convolved with the instrumentation profile, are overlaid on top of the observed PV diagrams. The lowest contours and contour intervals of both spectra are identical to those of Figure 2. The velocity centroids of the observed and synthetic spectra are shown at a STIS velocity resolution of $\sim 65$ km s$^{-1}$. The average velocities at the centroids of the synthetic spectra are $\sim -170$ km s$^{-1}$ for the blue and $\sim 110$ km s$^{-1}$ for the red, which reconfirm the velocity ratio of $\sim 1.6$, and the trend of slightly increasing velocities along the axes. In the case of [N ii], emission at the stellar position is missing from the blue jet. However, we cannot assess whether this is due to the nature of the weaker emission from the blue jet or other reasons.

The line intensities and image widths of the synthetic images cover the overall trends in the observed ones. The trends

![Figure 3](image-url)  
*Figure 3.* Optical line-ratio diagrams for the RW Aur A jet derived from the HST/STIS spectra. The blue jet is defined here by the integrated intensities over the velocity interval $[-250, -20]$ km s$^{-1}$ and the red jet is defined by those within $[+20, +200]$ km s$^{-1}$. In each panel, points labeled with the same color are sampled every 0.05 unless the fractional error of either line ratio is above 50%. Left: line ratios integrated over the central five slits at different distances along the jet. Right: line ratios obtained at different positions from the central five slits without integration. The innermost 0.95 of the blue jet and 0.65 of the red jet are shown for clarity. (A color version of this figure is available in the online journal.)

| Properties                | Symbol | Blue Jet | Red Jet | Unit |
|---------------------------|--------|----------|---------|------|
| Average terminal wind velocity | $\bar{v}_w$ | 310 | 200 | km s$^{-1}$ |
| Inclination angle          | $i$    | 55       | 55      | $^\circ$ |
| Disk truncation radius     | $R_x$  | 0.117    | 0.117   | AU   |
| Mass-loss rate             | $M_w$  | $3 \times 10^{-8}$ | $5 \times 10^{-8}$ | $M_\odot$ yr$^{-1}$ |
| X-ray luminosity           | $L_X$  | $6.0 \times 10^{31}$ | $9.9 \times 10^{31}$ | erg s$^{-1}$ |
| Mechanical heating coefficient | $\alpha_h$ | $1.0 \times 10^{-3}$ | $1.5 \times 10^{-3}$ |
The similarities and differences in the cross line-ratio diagrams between the synthetic maps and the actual data reveal the degree to which the physical conditions are reproduced by the model parameters. Figure 9 shows the line ratios between [N ii] 6583/[O i] 6300 and [S ii] 6731/[O i] 6300, and between [S ii] λ6716/6731 and [S ii] 6731/[O i] 6300 overlaid by model coverage (in color shades). The shaded areas include the innermost 0.95 of the blue jet and 0.65 of the red jet, at a distance ratio approximately proportional to their respective velocities. In the transverse direction, the model points extend to about $\sigma = 0.12$, corresponding roughly to the spatial coverage of the central three slits. The shaded areas generated by the synthetic images encompass most of the observed data points (in discrete symbols), following similar trends, up to the tips of the knots, B4 and R7. The overall ratio of [N ii] 6583/[O i] 6300 is about twice as large in the blue jet as in the red jet. As shown in Figure 5, the overall electron fraction of the blue wind is approximately twice as large as in the red wind. The spatial dependence of [S ii] 6731/[O i] 6300 varies with the differences in critical densities in [S ii] 6731 and in [O i] 6300, and the [S ii] doublet ratio varies across the jet as $n_e$ decreases faster laterally than longitudinally in the model. The combination of ($x_e, T$) in Figure 5, following our selection criteria of the solutions, indeed captures the overall sense of differences and asymmetry found on the opposite sides of the jet. The differences in excitation conditions within the opposite jet components differentiate the distribution of data points on the respective line-ratio diagrams.

Our synthetic points are distributed over a wider area than the observed points. This is because a large area is covered by fainter pixels in the computational domain. This is especially noticeable for the brighter red jet. The model points come from the equivalent area covered by the central three slits as small pixels. Emission from these theoretical pixels is ideally excited by the model approach outlined in Section 2.2. As each of the theoretical pixels contributes to the model line-ratio points, there may not be corresponding points from the observed data. This is because the actual jets are knottier than the ones in the model and some of the jet volume is not sufficiently excited in real space as in the model counterpart. This explains why the model naturally predicts a broader range of values in line ratios, while the observed range is narrower because the observations are naturally weighted toward the regions with strong emission. On the other hand, the observed data for the blue jet have much higher uncertainties because the jet itself is weaker in emission but faster in flow speed, which may result in a wider spread in physical conditions from the start. However, a rough trend can still be traced when all the slits are added to increase delineated by the theoretical curves capture the major features well up to locations where the observed knots become too faint. For the redshifted jet, the model profiles pass through the average of the knot peaks and off-knot regions; in the blueshifted jet, the same holds true for the intensity profiles, although for the image widths and velocity centroids, the curves pass through more scattered points except for [S ii] 6731. The image widths gradually increase with distance as the overall intensity profiles gradually decrease along the axes. This is expected as the electron fraction overall follows a pattern of recombination, as pointed out by Bacciotti et al. (1996) and SGSL.
Figure 5. Contours of the electron fraction (black lines) are shown on top of the temperature profiles (color map, in units of K), for the models listed in Table 5. The left panel is for the blue jet and the right panel is for the red jet.

4. DISCUSSION

4.1. General Features

We have attempted to re-analyze the set of archived HST/STIS data previously analyzed and published in Woitas et al. (2002) and Melnikov et al. (2009). Similar results were reached, in general, although with some noticeable differences in terms of the inferred physical quantities. Our methods of data analysis differ from those adopted in Melnikov et al. (2009), but are mostly similar to those adopted in Woitas et al. (2002). Melnikov et al. (2009) included further noise subtraction and correction of $A_V \approx 0.4$ throughout the jet. The remaining noise in our data could introduce more scatter for the line ratios in the blue jet, but the overall values are consistent since the line ratios in adjacent wavelengths can mitigate the effect of extinction to $\sim 10\%$ (Bacciotti & Eislöffel 1999). They also adopted a higher radial velocity for RW Aur A (+23.5 km s$^{-1}$) than the average value (+16.0 km s$^{-1}$). As expected, the line properties are nearly identical apart from the systematic velocity shift. On the results from the archived data, the overall properties one would generally infer from the opposite sides of the jet are not altered by different approaches and assumptions.

The physical conditions derived from the different diagnostic analyses, rather than the methods of data analysis, distinguish the various works based on the same set of data. Melnikov et al. (2009) derived the physical quantities using techniques developed by Bacciotti & Eislöffel (1999, the BE technique) for the individual jet without making a priori assumptions regarding the fainter blue jet as in Woitas et al. (2002). Melnikov et al. (2009) reached the conclusion that the blue jet is less dense and more excited than the red jet. The abundances of the atomic and ionic species involved are somewhat different, which may contribute to the theoretical line intensities and ratios through a combination of electron density, ionization fraction, and temperature. Comparing the physical conditions derived from our self-consistent approaches (Figures 4 and 5) and those derived from diagnostic mapping by employing the BE technique (Table 1 of Melnikov et al. 2009), we note differences in the values and relative trends. For example, electron densities derived from the BE technique are lower in the red jet by 20%. The faintness of the blue jet introduces larger uncertainties in the line ratios and in the derived electron densities. Values derived from the [S ii] doublet may also represent a lower limit due to its low critical density ($\sim 2.5 \times 10^3$ cm$^{-3}$). It can be seen in Figure 4 that the values for both jets are similar in the densest region, but that they decrease faster in the cylindrical distance $\sigma$ in the blue jet. From the ionization fraction and temperature, both works concluded that the blue jet is the more heated and
Figure 6. Images and spectra as observed and theoretical data are compared on top of each other in [O\textsc{i}] $\lambda$6300 (for the red jet) and [O\textsc{i}] $\lambda$6363 (for the blue jet). Left: variations of the peak intensity and the FWHM are plotted along the axes of jets, with their Gaussian fits from the synthetic images (thick lines). The red jet is shown in red and the blue jet is shown in blue. Observed data points are shown with filled red circles for the red jet and in filled blue squares for the blue jet. Right: the position–velocity diagrams extracted from the observed (black contours as in Figure 2) and synthetic (blue and red contours) spectra for the red and the blue jets in the upper panel. The Gaussian-fitted velocity centroids from the observed (filled blue and red symbols) and synthetic (thick blue and red lines) spectra are plotted in the lower panel, showing the distinct velocity ratio of $\sim$1.6.

(A color version of this figure is available in the online journal.)

Figure 7. Images and spectra as observed and theoretical data are compared on top of each other for [N\textsc{ii}] $\lambda$6583. Symbols are the same as those in Figure 6.

(A color version of this figure is available in the online journal.)
Figure 8. Images and spectra as observed and theoretical data are compared on top of each other for [S\ II] λ6731. Symbols are the same as those in Figure 6. (A color version of this figure is available in the online journal.)

Figure 9. Line ratios calculated from the blue jet and the red jet models (shaded areas) overlaid onto the observed data (discrete symbols). The discrete symbols and shaded areas have the same spatial coverage in x (0′′.12, roughly corresponding to the central three slits) and y (0′′.95 for the blue jet and 0′′.65 for the red jet). (A color version of this figure is available in the online journal.)
ionized, and the temperatures derived from the BE technique are typically 50% higher than those found in this work. The higher temperature may compensate for the lower inferred electron densities of the observed line intensities. The re-heating of the jet close to knot positions may raise the values locally. The derived ionization fraction from Melnikov et al. (2009) is in line with our values at the innermost streamlines where X-ray irradiation is the strongest (Figure 5). The hydrogen density that is derived by dividing the electron density with the electron fraction may weight toward the lower value, leading to mass-loss rates that could be lower by an order of magnitude (see below).

Physical properties such as the mass-loss rates inferred for the opposite sides of the jet are the best tests for the dynamical models and diagnostic analyses developed and integrated into the models. Our best-fit mass-loss rate for the red jet is in line with that found in Bacciotti et al. (1996) using line ratios, and those found in Hartigan et al. (1995) and White & Hillenbrand (2004) using forbidden line intensities. These values are of the same order as those in Woitas et al. (2002), but one order of magnitude larger than those derived by Melnikov et al. (2009). The small value in Melnikov et al. (2009) lies in their consideration of the “intrinsic” image widths. Although the jet radii appear more accurate, the mass loss carried by the associated wide-angle wind is not taken into account. It is also possible that the electron densities derived from the [S II] doublet represent a lower limit. On the other hand, the imbalance of momentum deduced from the ratio of mass-loss rates between the two sides of the jet is larger in Woitas et al. (2002). Specifically, Woitas et al. (2002) obtained the line-of-sight velocity, $v_j$, and jet width, $r_j$, from the same data set, and derived electron densities $n_e$ from the [S II] line ratio. They inferred a mass-loss rate $M_{\text{e}} = \mu m_H(n_e/x_e)\pi r_j^2/v_j/\cos i$, where the electron fraction $x_e$ of the red jet was adopted from Dougados et al. (2002), and the values in the blue jet were assumed to be similar to those in the red jet. They also assumed similar $\lambda 6583/[\text{O I}] \lambda 6300$ ratios for both sides, which led to the estimate of a mass-loss rate ratio of $\sim 2$ (blue to red). Similarly, a ratio of $\sim 3$ is derived for the momentum. Woitas et al. (2002) interpreted this as a temporary phenomenon occurring during accretion since there was no recoil velocity detected. Yet the discrepancy may be resolved if the adopted $x_e$ is two to three times higher in the blue jet, then the ratio of momentum rates from the two sides would be $\propto v_j^2/r_j \approx 1$ after correcting the ratio of the electron fraction. In addition, their analysis of the emitted fluxes gave mass-loss rates that decrease by more than one order of magnitude within a distance of $2''$, which they interpreted as a decrease in mass loss due to secondary push at internal working surfaces. Although they also acknowledged the possibility of a decrease in the electron fraction and a reduction of excitation, they left the unbalanced mass-loss and momentum rates unsolved. Our method self-consistently calculates the physical properties that best match the overall line intensities and line ratios, unbiased toward only the inner dense part, leading to a better estimate of the mass-loss rates and to a general balance in linear momentum.

The “excess” redshifted emission at the stellar position on the approaching side is difficult to assess due to the subtraction artifacts of the stellar continuum. Pyo et al. (2006) and Hartigan & Hillenbrand (2009) pointed out the high-velocity features of the RW Aur jet in [Fe II] $\lambda 1.644 \mu m$ at a velocity resolution of $\lesssim 30 \text{ km s}^{-1}$: narrow line widths at the jet proper, symmetric profiles at each position, and increasing line widths toward the source in general support the predicted PV diagrams shown in SSG, rather than the disk-wind models. On the other hand, they also commented that the original PV diagrams for an approaching X-wind jet, as shown in SSG, perhaps carry some “excess” redshifted emission extending over the stellar position toward the counter side. Hartigan & Hillenbrand (2009) suggested stronger heating (or re-heating) at a greater distance may resolve the discrepancy. The wide-angle wind would inevitably possess streamlines that contribute to the redshifted line-of-sight velocity, if the system is not strictly pole-on. We followed SSG and SGSL for the calculations of the line emissivities. The so-called excess is less pronounced in our maps generated for RW Aur A parameters with the self-consistent excitation conditions implemented, when compared to the original PV diagrams in SSG that were produced with uniform temperature and ionization throughout the wind. This might suggest that the inner streamlines in our system might have been slightly more excited than the wind case inside the RW Aur A system. With the 0.1 spatial resolution of HST, the emission is restricted to the stellar position within one resolution element, and this area is strongly affected by the artifact introduced by stellar baseline subtraction in rectified two-dimensional STIS spectra (see also Melnikov et al. 2009).

We have demonstrated the existence of a pair of X-wind solutions that could capture the major features of asymmetry in the RW Aur A system. The asymmetric properties reported in the literature and the archival HST/STIS data are confirmed by our analyses. The mass-loss rates that are required to best match the overall trends in the emission profiles and line ratios are also asymmetric: $M_R = 3 \times 10^{-8} M_\odot \text{ yr}^{-1}$ for the blue and $M_R = 5 \times 10^{-8} M_\odot \text{ yr}^{-1}$ for the red. These two mass-loss rates give a ratio of $M_B/M_R \approx 0.6$. Multiplied by the asymmetric terminal velocity ratio, $\bar{v}_R/\bar{v}_B \approx 1.6$, we reach a ratio of linear momenta of $M_B \bar{v}_R/M_R \bar{v}_R \approx 1$. This suggests that momenta ejected into the opposite hemispheres are indeed balanced. This is in contrast to the apparent dilemma of unbalanced momenta carried by the two jets from the velocity asymmetry reported in Woitas et al. (2002) and Melnikov et al. (2009). Despite the asymmetry in velocity, line intensities, and mass-loss rates, the system is on average balanced for the most important physical quantity.

The seemingly unequal mass loading and the uneven terminal velocities in the northern and southern hemispheres of RW Aur A do not break the law of conservation for linear momenta and magnetic fluxes contributed by the wind in our study. These major physical quantities are indeed conserved, in the average sense, across the opposite jets. From the analysis of emission lines originating from the jet alone, the conservation is an integral part of the original scenario and framework laid out in the first X-wind papers (Shu et al. 1994a, 1994b, 1995) and there is no need to invoke asymmetry beyond the immediate wind proper. There are also no obvious detectable precession or signatures from the precession of the jet that would suggest a non-alignment of the magnetic axis with the rotation axis in the physical properties and timescales of the existing data sets. However, we cannot rule out other possibilities from the star itself or processes of the star–disk interaction. On the other hand, if the timescales of variation are short, the effects of asymmetry originating deep in the star system might have been averaged over the rotation periods and a long flow time, such that the visual effects are small on a large scale. Further clues along these
lines are supported by other observational evidences, and will be discussed in a follow-up investigation.

4.2. Further Constraints

In this work, we have demonstrated the possibilities of finding a match between the X-wind models and the HST/STIS spectra of the RW Aur A jet, and discussed additional properties that were inferred from such a matching process. Although the existence of a set of solutions does not constrain a unique launch point $R_L$, the overall procedure suggests that general features of the X-wind models indeed match those obtained from the data analysis. In particular, the mass-loss rates and excitation properties not only fall nicely within the general range suggested by the data, but also solve the puzzling asymmetry in the physical properties of the system. Despite such ambiguity, the general results demonstrated in this work should hold in any model selected, given that a different combination with another $R_L$ provides a good fit with the detailed properties. The differences should be within a factor of two of what we learned in this work.

Currently available observational data on the RW Aur A jet do not seem to be able to resolve the ambiguity alone. Observational clues or constraints derived near the base of the jet related to the inner truncation radii of the disk or some other information inferred from the permitted lines originating in the accretion funnels may help to resolve the uncertainties. The inner truncation radii of the RW Aur A disk from near-infrared interferometry (Akeson et al. 2005; Eisner et al. 2007) have a range of 0.08–0.2 AU, consistent with fits of models with dust sublimation temperature between 1000 and 1500 K. The gas disk may extend to 0.02–0.05 AU (Eisner et al. 2009) inside the dust disk, although the actual values may be dependent on the underlying disk models adopted. These are all well within the possible choices for $R_L$ considered in this paper (Tables 3 and 4).

The recent Zeeman-splitting measurement of optical emission lines can help to qualitatively infer the magnetic structure of the interaction region between the star and the disk (Dodin et al. 2012). The average longitudinal magnetic field strength $B_z$ inferred from the narrow component of He i λ5876 was found to change polarity within one rotation period assuming $P = 5.576$ days. This is consistent with a model proposed in Petrov et al. (2001), which showed that the variation of lines is due to two hot spots on opposite poles of the star. The coronation radius corresponding to this period is $\sim 0.07$ AU assuming $M^* = M_\odot$. While this is still within our considerations, it also may be possible that the disk truncation radius ($\sim R_L$) does not always coincide with the coronation radius. In the case of a fluctuating X-wind (Shu et al. 1997), $\Omega_* \neq \Omega_c$, the disk truncation radius moves in and relative to the coronation radius. The magnetic energy released is proportional to the difference in angular frequency, and part of it may come out in X-rays. In this case, the X-ray activities may affect the initial ionization of the flow and properties of the lines. Simultaneous monitoring of both X-rays and photospheric and forbidden emission will be desirable in order to understand the star–disk interaction in the RW Aur A system.

5. SUMMARY

We have presented detailed analyses and comparisons between the HST/STIS archival data and synthetic spectra from the X-wind models for the bipolar jet of RW Aur A. We analyzed properties of optical forbidden lines [O i], [N ii], and [S ii] through PV diagrams, images, and line ratios. PV diagrams of all the lines show similar kinematic features and an average blue-to-red velocity ratio of $\sim 1.6$. Spectra of high spatial resolution enable diagnostics for both jets through the line ratios. We were able to identify the general properties related to the asymmetry of the physical conditions derived through the line ratios, and applied them as constraints for model comparisons.

The diagnostic approach developed in SGS&L was extended and applied to RW Aur A, using parameters for the stellar mass, radius, systemic velocity, and inclination angles of the jet and disk. Within observational uncertainties, we could select a set of stellar parameters to demonstrate a sample fitting process for illustration. Mass-loss rates, X-ray luminosities, and mechanical heating, the model parameters, were explored for a pair of X-wind solutions that were selected by matching the velocity ratio, starting with the fiducial models adopted in Shang et al. (2002, 2004, 2010). The combined models not only possess the feature of asymmetry in jet speeds but also simultaneously meet the overall agreement in line intensities, image widths, and line ratios.

Our interpretation of the RW Aur A system offers a different perspective to the driving of the asymmetric jets. For the many years since its discovery, the asymmetry in the opposite sides of the bipolar jet has intrigued astronomers. Previous analysis of the same STIS data set suggested a nearly equal mass-loss rate in the opposite jets themselves but with asymmetry in the ambient environment (Melnikov et al. 2009). Through the demonstration of a sample fit with the X-wind models, we are able to interpret the asymmetry in velocity and intensity to be a consequence of different mass loading on the opposite sides of the disk while the system adjusts itself to conserve linear momentum. Moreover, our analysis suggests that the jet and wide-angle wind system, as a whole, is one entity, since observational interpretation through the optical lines alone would not recover the entirety of the mass loss inside the hemisphere.

In this work we demonstrate that the framework of X-winds can accommodate many general features of asymmetric disk–jet systems such as RW Aur A. Analyses, such as the one presented here, may be applied to other similar systems. Further constraints of the disk–jet system through a high-dispersion spectral line diagnosis associated with the jet and accretion activities are strongly encouraged.

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Facility: HST (STIS)
REFERENCES

Akeson, R. L., Boden, A. F., Monnier, J. D., et al. 2005, ApJ, 635, 1173

Alencar, S. H. P., Basri, G., Hartmann, L., & Calvet, N. 2005, A&A, 440, 595

Bacciotti, F., & Eislöffel, J. 1999, A&A, 342, 717

Bacciotti, F., Hirth, G. A., & Natta, A. 1996, A&A, 310, 309

Beckwith, S. V. W., & Sargent, A. I. 1993, ApJ, 402, 280

Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883

Cabrit, S., Pety, J., Pesenti, N., & Dougados, C. 2006, A&A, 452, 897

Cai, M. J., Shang, H., Lin, H.-H., & Shu, F. H. 2008, ApJ, 672, 489

Cai, W., & Pradhan, A. K. 1993, ApJS, 88, 329

Dodin, A. V., Lamzin, S. A., & Chountonov, G. A. 2012, Astron. Lett., 38, 167

Dougados, C., Cabrit, S., & Lavalle-Fouquet, C. 2002, Rev. Mex. Astron. Astrophys. (Ser. Conf.), 13, 43

Dougados, C., Cabrit, S., Lalvalley, C., & Ménard, F. 2000, A&A, 357, L61

Eissner, J. A., Graham, J. R., Akeson, R. L., & Najita, J. 2009, ApJ, 692, 309

Eissner, J. A., Hillenbrand, L. A., White, R. J., et al. 2007, ApJ, 669, 1072

Garcia, P. J. V., Cabrit, S., Ferreira, J., & Binette, L. 2001, A&A, 377, 609

Getman, K. V., Feigelson, E. D., Broos, P. S., Micela, G., & Garmire, G. P. 2008, ApJ, 688, 418

Hamann, F. 1994, ApJS, 93, 485

Hartigan, P., Edwards, S., & Ghandour, L. 1995, ApJ, 452, 736

Hartigan, P., & Hillenbrand, L. 2009, ApJ, 705, 1388

Hartigan, P., Strom, K., & Strom, S. 1994, ApJ, 427, 961

Hartmann, L., Hewitt, R., Stahler, S., & Mathieu, R. D. 1986, ApJ, 309, 275

Hirth, G. A., Mundt, R., & Solf, J. 1997, A&AS, 126, 437

Hirth, G. A., Mundt, R., Solf, J., & Ray, T. P. 1994, ApJ, 427, L99

Kenyon, S. J., Dobrzycka, D., & Hartmann, L. 1994, AJ, 108, 1872

Kenyon, S. J., & Hartmann, L. 1995, ApJS, 101, 117

López-Martín, L., Cabrit, S., & Dougados, C. 2003, A&A, 405, L1

McCleary, J. E., & Wolf, S. I. 2011, AJ, 141, 201

McGourty, F., Ray, T. P., & Froebrich, D. 2007, A&A, 467, 1197

Melnikov, S. Yu, Eislöffel, J., Bacciotti, F., Woitas, J., & Ray, T. P. 2009, A&A, 506, 763

Mendoza, C. 1983, in IAU Symp. 103, Planetary Nebulae, ed. D. R. Flower (Dordrecht: Reidel), 143

Mundt, R., & Eislöffel, J. 1998, AJ, 116, 860

Petrov, P. P., Gahm, G. F., Gameiro, J. F., et al. 2001, A&A, 369, 993

Pyo, T.-S., Hayashi, M., Kobayashi, N., et al. 2006, ApJ, 649, 836

Ray, T. P., Mundt, R., Dyson, J. E., Falle, S. A. E. G., & Raga, A. C. 1996, ApJ, 468, L103

Reipurth, B., & Bally, J. 2001, ARA&A, 39, 403

Shang, H. 1998, PhD thesis, Univ. California, Berkeley

Shang, H., Glassgold, A., Lin, W.-C., & Liu, C.-F. 2010, ApJ, 714, 1733 (SGLL)

Shang, H., Glassgold, A. E., Shu, F. H., & Lizano, S. 2002, ApJ, 564, 853 (SGLS)

Shang, H., Lizano, S., Glassgold, A., & Shu, F. 2004, ApJ, 612, L69 (SLGS)

Shang, H., Li, Z.-Y., & Hirano, N. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 261

Shang, H., Shu, F. H., & Glassgold, A. E. 1998, ApJ, 493, L94 (SSG)

Shu, F., Najita, J., Ostriker, E., & Shang, S. 1995, ApJ, 455, L155

Shu, F., Najita, J., Ostriker, E., et al. 1994a, ApJ, 429, 781

Shu, F., Najita, J., Ruden, S., & Lizano, S. 1994b, ApJ, 429, 797

Shu, F. H., Najita, J. R., Shang, H., & Li, Z.-Y. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson, AZ: Univ. Arizona Press), 789

Shu, F. H., & Shang, H. 1997, in IAU Symp. 182, Herbig-Haro Flows and the Birth of Stars, ed. B. Reipurth & C. Bertout (Dordrecht: Kluwer), 225

Shu, F. H., Shang, H., Glassgold, A. E., & Lee, T. 1997, Science, 277, 1475

Stout-Batalha, N. M., Batalha, C. C., & Basri, G. S. 2000, ApJ, 532, 474

White, R. J., & Ghez, A. M. 2001, ApJ, 556, 265

White, R. J., & Hillenbrand, L. A. 2004, ApJ, 616, 998

Woitas, J., Bacciotti, F., Ray, T. P., et al. 2005, A&A, 432, 149

Woitas, J., Leinert, Ch., & Köhler, R. 2001, A&A, 376, 982

Woitas, J., Ray, T. P., Bacciotti, F., Davis, C. J., & Eislöffel, J. 2002, ApJ, 580, 336