INTEGRAL-FIELD SPECTROSCOPY OF THE POST–RED SUPERGIANT IRC +10420:
EVIDENCE FOR AN AXISYMMETRIC WIND

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ABSTRACT

We present NAOMI / OASIS adaptive-optics-assisted integral-field spectroscopy of the transitional massive hypergiant IRC +10420, an extreme mass-losing star apparently in the process of evolving from a red supergiant toward the Wolf-Rayet phase. To investigate the present-day mass-loss geometry of the star, we study the appearance of the line emission from the inner wind as viewed when reflected off the surrounding nebula. We find that, contrary to previous work, there is strong evidence for wind axisymmetry, based on the equivalent width and velocity variations of Hα and Fe II λ6561. We attribute this behavior to the appearance of the complex line profiles when viewed from different angles. We also speculate that the Ti II emission originates in the outer nebula in a region analogous to the strontium filament of η Carinae, based on the morphology of the line emission. Finally, we suggest that the present-day axisymmetric wind of IRC +10420, combined with its continued blueward evolution, is evidence that the star is evolving toward the B[e] supergiant phase.

Subject headings: circumstellar matter — stars: evolution — stars: individual (IRC +10420) — stars: mass loss — stars: winds, outflows — supergiants

Online material: color figures

1. INTRODUCTION

IRC +10420 (α = 19h26m48.0s, δ = 11°21′16.7″, J2000.0) is an extremely luminous star that inhabits the so-called yellow void on the HR diagram between the red and blue supergiants (de Jager 1998). There is considerable evidence that the star is evolving rapidly away from the RSG phase toward the luminous blue variable (LBV) or Wolf-Rayet (W–R) phases (see below). As such, this object represents a potential link between the key post-main-sequence mass-losing stages and is therefore considered extremely important for the study of massive stellar evolution.

The star is surrounded by a dusty circumstellar nebula, responsible for its large IR excess. This nebula is the result of an extreme mass-losing episode in the RSG phase, when the mass loss reached \( \geq 10^{-4} \text{ M}_{\odot} \text{yr}^{-1} \) (Oudmaijer et al. 1996, hereafter O96). It is also an OH maser source, a phenomenon usually identified with much cooler stars (Giguere et al. 1976). This maser is thought to be a relic of an earlier M supergiant phase, from which the central star must have rapidly evolved on a timescale of \( \leq 10^5 \text{ yr} \) in order for the maser source to still survive (Mutel et al. 1979). Indeed, the star has been observed to gradually increase in temperature from \( \sim 6000 \) to \( \sim 9200 \text{ K} \) in the last 30 years (O96; Klochkova et al. 2002).

The material the star has recently ejected may be the precursor to a LBV/W–R nebula. These nebulae are often axisymmetric, but it is unclear how these nebulae are formed. Hydrodynamical studies have shown that axisymmetric morphologies can arise from either an axisymmetric wind in the LBV/W–R phase, or a spherically symmetric wind plowing into a slower axisymmetric wind ejected in the RSG phase (Frank et al. 1995; Dwarkadas & Owocki 2002). As wind axisymmetry may be linked to rotation, which itself plays an important role in the evolution of a massive star (see, e.g., review of Maeder & Meynet 2000), and as IRC +10420 appears to be somewhere between the LBV/W–R and RSG phases, determining the true geometry of the star’s present-day wind may provide insight into the formation mechanism of the bipolar nebulae of massive stars. Further, it may also provide clues as to the role of rotation in the subsequent evolution and the connection to other classes of massive star.

The geometry of IRC +10420’s wind has been the topic of much discussion over the last \( \sim 20 \) years, yet a common consensus remains elusive due to the weight of apparently contradictory evidence. The OH maser emission was spatially resolved by Diamond et al. (1983), who suggested the masering originated in an equatorial outflow seen almost edge-on. In the mid 1980s, the star began to show Hα emission (Irvine & Herbig 1986), high-resolution observations of which showed it to be doubly peaked (Jones et al. 1993)—reminiscent of classical Be stars, which are commonly thought to have outflowing disks (Porter & Rivinius 2003). In addition, Jones et al. argued that while the star has considerable IR excess, there is only modest extinction toward the central star. This, they concluded, was due to the circumstellar material being located in an inclined disk, with the star itself relatively unobscured. Also, their mid-IR imaging was elongated at a position angle (P.A.) of \( \sim 150^\circ \), which they suggested was the P.A. of the disk.

However, from near-infrared spectra, Oudmaijer et al. (1994) argued that the Hα emission was inconsistent with a circumstellar disk, suggesting instead that the ionized material was located in a bipolar outflow oriented close to the line of sight. Humphreys et al. (1997) argued for bipolarity of the outer nebula, and that the morphology was analogous to that of the dusty homunculus nebula around η Car oriented almost pole-on. They suggested the extended emission to the southwest was due to the nearer lobe, while the receding lobe on the far side to the northeast was obscured by equatorial material.

The confusion was apparently complete when Humphreys et al. (2002), using Hubble Space Telescope (HST) STIS long-slit spectroscopy, utilized the star’s reflection nebula as a tool with which to view the Hα emission from different angles. With the slit
aligned along the long axis of the nebula, they showed that the velocities of the two peaks in their Hσ profile were “surprisingly uniform.” This they argued was inconsistent with a circumstellar disk or a bipolar outflow, and concluded that the star showed no evidence of axisymmetry in the present-day wind.

However, Humphreys et al. only observed two slit positions, each roughly parallel to the long axis of the nebula and separated by 0.5″. In this paper, their data are improved on with spatially resolved spectroscopy across the whole of the inner nebula, with integral-field spectroscopy. We will show that, contrary to the conclusions of Humphreys et al., the emission lines are variable when viewed from different angles. It is argued that this is due to the nonisotropic nature of the star’s wind, and that the line emission is formed in an axisymmetric structure in the inner wind.

We begin in §2 with a description of the observations, data reduction steps and analysis techniques. The results of the data analysis are presented and discussed in §3, and summarized in §4.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

Data were taken during 2005 September 3–5 at the William Herschel Telescope on La Palma, using OASIS in Tiger mode (Bacon et al. 1995) in conjunction with the NAOMI adaptive optics system (Myers et al. 2003). Observing conditions were good, with a small amount of extinction (~few tenths of 1 mag) due to Saharan dust. Seeing was 0.6–1.0″ throughout our program.

The 22 mm enlarger was used in conjunction with the HR667 filter, which gives a plate scale of 0.97 Å pixel−1 in the wavelength range 6490–6840 Å and a lenslet size of 0.26″.

In addition to the usual calibrations of biases, dome flats, and neon arcs, the following extra calibration exposures must be taken for OASIS—undispersed micropupil frames, which record the positions of the micropupils focussed by the lenslet arrays onto the CCD; and continuum frames, which record the positions of the spectral “ridges” on the CCD. These calibrations were done by illuminating the lenslets with a tungsten bulb.

For the science frames the observational strategy employed was that of exposures with increasing integration times, to gradually increase the signal-to-noise ratio (S/N) in the outer parts of the field of view while obtaining unsaturated data at the center of the image. Exposures were dithered by ~0.1″ to identify and reject bad pixels on the CCD. Overall, 6 hr of science exposures were obtained in 17 separate exposures.

In addition, a PSF standard star, HIP 95166, was observed in order to accurately measure the PSF at the time of observations. The standard is separated from IRC +10420 by 1.3″, has brightness V = 10.4 compared with V = 11.1 for IRC +10420.

In practice, even the longest exposure times of 30 minutes only just saturated the Hσ line in the central couple of pixels. However, the MITT3 CCD is very susceptible to cosmic rays, and long-exposure images were so decimated by cosmic hits that the spectral mask creation algorithm failed in the outer regions where the S/N is lower. Subsequently, some data had to be discarded. Therefore, for future observations using this setup, integration times of no longer than ~15 minutes are recommended.

2.2. Data Reduction

All data reduction was done with the instrument’s custom-written software XOASIS,4 and following the steps outlined in the software documentation. Initially, a median-averaged bias frame was subtracted from all calibration and science frames. A spectral “mask” was created using the micropupil and continuum frames, which recorded the loci of each micropupil spectrum on the detector. This mask was used to extract each spectrum of a given exposure, which were arranged in a data cube with the spatial coordinates of the corresponding lenslet.

Each spectrum in a single-exposure data cube was flat-fielded with the corresponding spectrum in the master continuum-lamp data cube. Wavelength calibration was done by fitting a second-degree polynomial to the five identified neon lines in the observed wavelength range. When identifying and rejecting cosmic rays, it was found that the XOASIS algorithm was unable to deal with the high number of hits without attacking the Hσ line center. Instead, cosmic rays were rejected at the mosaicing stage.

To mosaic the 17 individual frames, each were first centered about the brightness center of each exposure. The frames were weighted according to the mean number of counts per frame, and resampled onto a square spatial sampling grid using bicubic interpolation. The median spectrum was then found at each spatial point on the grid, thus eliminating cosmic-ray hits. As the observations were dithered by ~0.1″, we chose to spatially sample the individual frames onto a master grid of 0.13″ pixel−1, i.e., half the size of a lenslet.

2.3. Data Analysis

The continuum of each spectrum was fitted with a second-degree polynomial, using only those regions deemed to be featureless from the high-S/N integrated over the whole field. Thus, a data cube of the continuum at each spatial pixel was created.

The discrete features of the spectral lines—see, e.g., Oudmaijer (1998)—are poorly resolved in these data, so spatial variations in line velocities were measured by fitting Gaussian profiles to the lines in each spectrum of the data cube. In order to test the uniformity of the instrumental spectral resolution, this analysis was applied to the neon arc frames. It was found that the spectral resolution was 60 ± 5 km s−1 over the whole chip.

Synthetic narrowband images were created by first summing the spectra in the data cube over the width of the line. The corresponding continuum was found by summing over the same spectral region in the “continuum cube” (the continuum fit to the data cube, see above). The “pure” line image was then found by subtracting the “continuum” image from the “continuum+line” image.

For PSF characterization and subtraction, the spatial PSF of the observations was assumed to be that of the standard star. As no spectral information was required of this object, the spectra of the standard were aggressively cleaned for cosmic rays and then median averaged in the spectral direction to produce a two-dimensional image. This was then resampled onto the same spatial grid as the target object. The FWHM of this image was found to be ~0.5″. This corresponds to a Strehl ratio of ~0.1, and an improvement of a factor of 2 on the seeing conditions. This is consistent with the expected performance of NAOMI at optical wavelengths. Qualitative PSF-subtraction was done by iteratively scaling the flux of the PSF standard with the flux of the science target, until cancellation effects at the center of the image were minimized.

3. RESULTS AND DISCUSSION

In this section the results of the data cube analysis are presented and discussed. All spatial images shown are centered on α = 19h26m48.0s, δ = 11°21′16.7″ (J2000.0), with north at the top and east to the left. To aid the interpretation of the data, the images are overlayed with a contour map of a HST F451M image

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4 See http://www.cfht.hawaii.edu/Instruments/Spectroscopy/OASIS/Reduc.
taken from the archive, with a spatial resolution of ~0.1\arcsec. As the image was taken in the blue part of the spectrum, the reflection nebula is clearly seen.

### 3.1. Mean Spectrum of IRC +10420

The spectrum over the full wavelength range observed and integrated over the whole image is shown in Figure 1. The individual spectra were flux-weighted before adding, and continuum-flattened later. In addition to the strong H\alpha line, the permitted lines of Fe \(\text{II} \lambda 6516\) and Ti \(\text{II} \lambda 6680, 6717\) are identified. Also, there are several unidentified features. The emission bump on the blue side of the diffuse interstellar band (DIB) at \(\lambda 6614\) is identified by Chentsov et al. (1999) as a blend of Sc \(\text{II}\) and Ti \(\text{II}\). The other unidentified spectral features are not present in Oudmaijer's 1994 spectrum. The properties of observed spectral features of the central region (region e in Fig. 2) are listed in Table 1.

![Fig. 1.—Spectrum of IRC +10420, integrated over the whole field of view. The lighter line in the bottom panel shows the spectrum magnified to highlight the weaker features.](image)

![Fig. 2.—Definition of the nine spatial regions over which the spectra were integrated.](image)

| \(\lambda_{\text{hel}}\) (Å) | Identification | \(W_j\) (Å) | \(v_{\text{hel}}\) (km s\(^{-1}\)) | FWHM (km s\(^{-1}\)) |
|-----------------|--------------|----------|-----------------|-----------------|
| 6508.08\ldots
| a
| +0.16
| ... 198 |
| 6517.39\ldots
| Fe \(\text{II}\)
| -1.0
| +62 151 |
| 6564.57\ldots
| H\alpha
| -50.2
| +80 372 |
| 6594.90\ldots
| [Ti \(\text{II}\)]?
| -0.04
| +90 109 |
| 6607.07\ldots
| b
| -0.28
| ... 193 |
| 6613.53\ldots
| DIB
| +0.23
| +1 177 |
| 6618.64\ldots
| c
| -0.15
| ... 199 |
| 6627.51\ldots
| c
| -0.12
| ... 195 |
| 6660.59\ldots
| DIB
| +0.09
| -2 108 |
| 6664.08\ldots
| d
| -0.08
| ... 167 |
| 6680.53\ldots
| Ti \(\text{II}\)
| -0.30
| +25 249 |
| 6719.02\ldots
| Ti \(\text{II}\)
| -0.14
| +50 171 |

**Notes:** These features are marked as \(a\) in Fig. 2. Col. (1): the measured line centers are in the heliocentric frame; col. (2): line identifications if any (see notes below); col. (3): equivalent width, with error ±5% determined from repeatability of measurements when different continuum points either side of the line were used; col. (4): heliocentric radial velocity, with error taken to be ±5 km s\(^{-1}\) ±0.1 pixels; col. (5): FWHM of a Gaussian fit to the line, with error ±5% determined from repeatability of measurements.

\(a\) = Unidentified line, Ne \(\text{i}\)?

\(b\) = Resolved in Oudmaijer (1998) as four discrete components, and in Chentsov et al. (1999) as two. Identified by the latter as a blend of Sc \(\text{II}\) and Ti \(\text{II}\).

\(c\) = Unidentified lines, may be split components of the same line; see \S 3.5.

\(d\) = Unidentified line, possibly a blend of Fe \(\text{II}\) and/or [Ni \(\text{II}\)]?

\(e\) = Possible unresolved blend of Ti \(\text{II}\) and He \(\text{i} \lambda 6678\).

The spectral features identified in Table 1 do not all exhibit the same behavior across the field. Below, we emphasize this by showing the residual spectrum between the central star and the surrounding nebula. This is followed by a discussion of the behavior of individual lines. As the S/N of the lines falls off with distance from the star, this analysis is limited to those with the highest S/N, in order to assess the spatial variations over as large a field as possible. These features are the H\alpha, Fe \(\text{II}\), and Ti \(\text{II}\) emission lines, as well as the unidentified blend at \(\sim 6610\) Å and the DIBs.

#### 3.1.1. Residual Spectrum of Central Object

In order to find the differences between the spectra of the central object and the surrounding nebula, we divide the field up into nine spatial regions: a central (star+nebula) region, surrounded by eight nebula regions (illustrated in Fig. 2). The spectra of the outer regions were added together and normalized by the mean continuum spectrum of the same regions, to ensure that the total “nebular” spectrum is weighted toward the higher S/N regions. The normalized spectrum of the central region (region e in Fig. 2) was then divided by the total nebular spectrum.

The resulting spectrum is shown in Figure 3. While the DIBs are seen to vanish, the Ti \(\text{II}\) lines remain, as does the unidentified line at \(\sim 6607\) Å. The features around the H\alpha and Fe \(\text{II}\) lines result from the ratio of lines of different width and velocities. In the following sections, the lines are individually discussed in more detail.

#### 3.2. Diffuse Interstellar Bands

There are three DIBs in the spectral region covered—one in the red wing of H\alpha at 6614 Å and two in the region of the Ti \(\text{II}\) lines at 6661 and 6700 Å. Figure 3 shows that these lines all cancel out perfectly in the residual spectrum between the star...
and the surrounding nebula. Analysis of the DIB at 6700 Å, the only DIB which appears not to be blended with other spectral features, shows that the equivalent width of the line is constant over the field to within the errors. However, the S/N in the outer regions is low, and for this reason it is not illustrated here.

The cancellation of the DIBs in the residual spectrum is an important result. These features are indicative of the interstellar extinction toward IRC +10420 (Oudmaijer 1998), and appear to be equally strong toward the central star and the outer nebula. This supports the conclusions of Jones et al. (1993), who found that, while the star has significant IR excess, there is only a relatively small amount of circumstellar extinction in the line of sight to the central star. In addition, this result strongly suggests that any variations observed in other spectral features are real.

3.3. The Hα and Fe II λ6516 Emission

The Hα and Fe II emission, as traced by the continuum-subtracted, PSF-subtracted images, closely follow the morphology of the reflection nebula as shown in the continuum B-band HST image (see Fig. 4). A star with $T_{\text{eff}} \sim 9200$ K is unlikely to emit enough flux shortward of 912 Å to ionize the circumstellar material out to these distances ($\sim 0.1$ pc if $D = 6$ kpc is assumed). It is therefore more likely that the line emission forms close to the star, and the light seen from the nebula is reflected. Further, it can be argued that the line emission is unresolved by the nebula: from modeling of speckle interferometry observations, Blöcker et al. (1999) found an inner dust radius of 70 $R_e$, meaning that the star has an apparent radius of $\sim 50$ when viewed from the inner dust wall. If all line emission forms within a few stellar radii, it is reasonable to assume that the line formation regions are spatially unresolved when viewed at the distance of the circumstellar dust.

3.3.1. Variations in Line Strength

With this in mind, we analyze the equivalent width ($W_j$) variations of the two lines. We note that the spectral resolution of this data ($\sim 60$ km s$^{-1}$) is not sufficient to resolve the double-peaked profile in Hα observed by Humphreys et al. (2002). However, the spectral resolution does not affect the equivalent width $W_j$. Therefore any variation in $W_j$ cannot be an artifact of unresolved features but instead must be due to a genuine change in line profile or line strength across the field of view. The stark uniformity observed in the DIBs (see § 3.2) would suggest that any observed variations are real.

A map of $W_j$ (Hα), shown in Figure 5, illustrates that there is a marked decrease of $\sim 15$ Å (25%) along the long axis of the nebula from southwest to northeast. We note that the same behavior is observed in the Fe II line, but at poorer S/N (not shown). This is clear evidence of a degree of axisymmetry to IRC +10420’s present-day wind.

This result is in direct contradiction to the conclusions of Humphreys et al. (2002). In their long-slit spectra, they observed that the velocities of the two peaks of the Hα profile were roughly consistent at several slit positions along the axis of the nebula. However, their slit positions happened to be oriented more or less along regions of the nebula where the Hα $W_j$ is constant to within $\sim 5$ Å. They therefore may have discounted any observed trend in $W_j$ as being too small to draw any conclusions from.

3.3.2. Variations in Velocity Centroid

As argued above, it is a valid assumption that formation regions of the Hα and Fe II lines in the stellar wind are point sources when viewed by the nebula. As the discrete components of the line profiles are unresolved in our data, at first thought one could assume that any shifts in the velocity centroids of the lines may
3.3.3. Anisotropic Emission?

While asymmetry in the dynamics of the reflection nebula alone could explain the variations in line centroid, it cannot explain the variations in line strength. Further, if the Hα and Fe II emission regions are roughly coincident (i.e., unresolved by the reflection nebula), the “moving mirror” could not explain why different velocity trends are observed in the two lines.

If the line emission seen by the dust is spatially unresolved, but the line profile had a different appearance depending on the viewing angle to the star, this would influence the observed velocity of the line when reflected off different regions of the nebula. The velocity maps shown above were created by fitting Gaussian profiles to the emission lines. This is a valid assumption as the line structure seen in high-resolution spectra is not resolved in this data. However, if the line profiles are complex and anisotropic, the unresolved line profile may seem to be velocity-shifted when observed from different viewing angles due to changes in the contributions from the different components. An example of this is described below.

Oudmaijer (1998) showed in his 1994 spectrum that various Fe II lines showed inverse P Cygni profiles, which he attributed to infalling material. In some line profiles, the absorption component was as strong as the emission component. The separation of the components was \( \pm 60 \text{ km s}^{-1} \), and so would not necessarily be resolvable in the data presented here. If the absorption component varied in strength depending on the viewing angle, for example due to an increased column density of infalling material, it may cause the peak of the total line profile to shift. An increase in redshifted absorption would cause the peak to shift to the blue, as well as producing an overall drop in equivalent width.

Similarly, the Hα emission is known to be doubly peaked, with the blue peak typically stronger than the red (e.g., Oudmaijer 1998; Humphreys et al. 2002). If the ratio of the two peaks, or the depth of the central absorption, were to depend on viewing angle, this could also cause an observed velocity trend in the unresolved emission line, as well as a change in total line emission.

The spectral resolution of our observations is not sufficient to provide a detailed view of how the line profiles change when viewed from different angles; however, from the unambiguous changes in line emission as probed by the \( W_2 \) map, and the differing velocity trends of the Hα and Fe II lines, we can say that strong evidence exists that the wind has an axisymmetric appearance when viewed from the surrounding reflection nebula.

Now the angle of axisymmetry has been better constrained, at least in terms of the Hα emission, it would be interesting to follow-up this study with high spectral resolution data similar to that presented in Humphreys et al. (2002) but with the slit position...
such as Sr $\upiota$ and Ti $\upiota$, to exist over an extended region without becoming doubly ionized. Further, the region must be very dense in order to produce significant Sr emission, due to its low cosmic abundance (a factor of $\sim 10^4$ lower than Fe) (Bautista et al. 2002).

Such a situation may exist in IRC +10420. The Ti $\upiota$ emission may originate in a region located within the nebula at a distance of $\geq 0.01$ pc ($D_\star = 5$ kpc) along our line of sight, shielded by the H and Fe in the inner wind. This would explain why the H and Fe line images trace the reflection nebula, while the Ti emission, which originates from the near side of the nebula, is essentially unseen by the rest of the nebula.

We note that this phenomenon may be less unusual in the case of IRC +10420. The star emits less radiation in the UV than $\eta$ Car, and so less shielding is required for the partially ionized zone to survive. Also, we have no geometry information on the other characteristic Sr filament lines of Sr $\upiota$ V $\upiota$, and Fe $\upiota$ emission, which are present in IRC +10420’s spectrum (Oudmaijer 1998). It would be interesting to compare the data presented here with similar data that could explore the emission regions of these lines, to confirm that they originate in the outer nebula.

3.5. On the Unidentified Blend around the DIB at 6614 Å

The nature of the spectral features around the 6614 Å DIB are unknown, but display considerable variations across the observed field (see Fig. 8). The bump of emission blueward of the DIB at 6614 Å is resolved in Oudmaijer (1998) as four separate emission peaks (see his Fig. 5). This is suggested by Oudmaijer to be a blend of Fe $\upiota$, although Humphreys et al. (2002) suggests one line may be that of Sc $\upiota$. The feature is resolved as two peaks of similar strength in the 1998 spectrum of Chentsov et al. (1999), who suggest line identifications of Sc $\upiota$ 6605 and Ti $\upiota$ 6607.

By taking a slice across the data cube at a P.A. of 33° i.e., aligned with the symmetry identified from the H$\alpha$ $W_2$ map, a synthetic long-slit spectrogram of this feature was created (see Fig. 9). The figure shows the feature on the blue side of the DIB apparently behaving identically to the Ti $\upiota$ lines, i.e., concentrated in the center of the field. This is strong evidence that this feature is in part due to Ti $\upiota$ emission, as suggested by Chentsov et al. (1999). This feature completely vanishes to the south, implying that all the unidentified, unresolved emission components which make up this feature behave in the same way.

The spectrogram of this region also reveals the behavior of the unidentified feature on the red side of the DIB. This feature is strongest $\sim 0.5''$ below the center, disappears, then reappears further south. The fact that it is apparently absent elsewhere in the field may explain why this feature has never been previously identified, as it is swamped by the rest of the emission when integrated over a large region.

There is a possibility that must be discussed, that the features on the red and blue side of the DIB are velocity-shifted components of the same transition, formed in, for example, a bipolar flow viewed pole-on (see conclusions of Oudmaijer 1998). The velocity separation of the two lines, which in this case is 450 km s$^{-1}$, would be centered on the systemic velocity of $\sim 75$ km s$^{-1}$ (Oudmaijer 1998), and implies an outflow velocity of 225 km s$^{-1}$. This means the rest-frame wavelength of the transition would be 6611.21 ± 0.16 Å, neglecting any uncertainty in the systemic velocity.

As such behavior is observed neither in H$\alpha$ nor in the singly ionized metallic lines of Fe and Ti, and as one may expect greatly different physical conditions within the bipolar flow to the rest of the wind, one would expect this transition to be from a high-ionization species. The only such line in this narrow region is

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**3.4. The Ti $\upiota$ λ6680, 6718 Emission**

Although weak, it is clear that the behavior of these lines differs from H$\alpha$ and Fe $\upiota$ λ6516. Figure 7 shows the continuum-subtracted, PSF-subtracted line image when the light of the two lines is combined. The behavior of each of the lines is similar, therefore we combined the two to increase S/N.

Unlike the H$\alpha$ and Fe $\upiota$ lines, the morphology of the reflection nebula is not reproduced by the Ti $\upiota$ line images. This is not due to low S/N, as it can be seen in both the H$\alpha$ and Fe $\upiota$ images that the S/N follows the contours of the nebula in the HST image (Fig. 4). This would seem to suggest that the emission zone of these lines is very different to that of the other lines studied, as discussed below.

**3.4.1. The Origin of the Ti $\upiota$ Emission**

If the reflection-nebula paradigm is to hold, then the only reason that the Ti $\upiota$ emission is not reflected off the nebula is if the line forms within or outside the nebula, in a localized region along our line of sight but a large distance from the central star. This would also explain the radial velocities being blueshifted by $\sim 25$ km s$^{-1}$ compared to the systemic velocity. If correct, this would mean that the Ti $\upiota$ emission originates at a distance $\sim 0.05$ pc ($D_\star = 5$ kpc) from the star.

It may be that the Ti $\upiota$ emission comes from a region analogous to the strontium filament in the nebula of $\eta$ Car (Zethson et al. 2001). This is a localized region located in the equatorial “skirt” of $\eta$ Car’s homunculus nebula, which shows very unusual spectral features of singly ionized Sr, Ti, and V among others, while showing no detectable H or He emission and only very weak Fe $\upiota$ emission (Hartman et al. 2004). It also a source of NH$_3$ emission, but no H$_2$ emission is observed (Smith et al. 2006).

The proposed explanation for the presence of $\eta$ Car’s Strontium filament is that the emission region must be bathed in photons with $5$ eV $\leq E_{ho} \leq 11$ eV (the ionization potentials of Sr and Ti are 5.7 eV and 6.8 eV, respectively), but is shielded from the intense radiation shortward of $\sim 1500$ Å by H and Fe $\upiota$ in the inner wind. This allows species with low ionization potentials...
The presence of Ti \textsc{iii} \lambda 6611.38 emission is not noted anywhere in the high-resolution spectra of (Oudmaijer 1998) and Chentsov et al. (1999). This line identification is therefore unlikely. Further study of this feature with high S/N, high spectral resolution data is warranted to investigate the "jet" nature of this feature.

3.6. The Significance of Wind Axisymmetry in IRC +10420

A wealth of evidence now exists for axisymmetry in the wind of IRC +10420 on several scales: from the outer reflection nebula seen in HST images (P.A. \(\sim 33^\circ\)), high-resolution IR images on scales of 1"–2" (\(\sim 58^\circ\); Humphreys et al. 1997), to the scales of a few stellar radii probed by spectropolarimetry (\(\sim 150^\circ\); Patel et al. 2008). The axes of symmetry of these observations are all either aligned or perpendicular to 45° ± 15°.

The data presented in this paper are consistent with this story. The quality of our data is such that we cannot resolve the changes in line profile when viewed from different angles, and so cannot draw any conclusions as to the geometry of the wind (e.g., disk or bipolar outflow) or density contrasts between equator and pole.
However, the $W_L$ and velocity variations of the H$\alpha$ and Fe $\pi$ lines provide clear evidence for wind axisymmetry, independent of the geometry of the reflection nebula. The position-angle of this axisymmetry is consistent with the long axis of the nebula ($\sim$33$^\circ$).

The axisymmetric wind of the star is strong evidence that rotation has played a significant role in its evolution, whereby a latitude-dependent effective gravity leads to very different mass-loss behavior between the equator and poles. This rotation could be due either to the presence of a companion, or merely fast initial rotation of the star. A rotating star that is losing mass is also losing angular momentum, and hence the equatorial surface gravity should steadily increase over time as mass is lost and the star spins down. This may cause the mass-loss rate to decrease as a function of age.

Studies of the star’s dust emission by O96 and Blöcker et al. (1999) have concluded that the mass-loss rate has decreased over time by factors of 15–40, while Lipman et al. (2000) also found a density gradient consistent with a falling mass-loss rate. In addition, Smith et al. (2004) suggest that the gradual increase of the star’s effective temperature over the last ~20 years or so (O96, Oudmaijer 1998; Klochkova et al. 2002) may be in fact due to a further decrease in mass loss. Here, the dense wind forms a pseudophotosphere, making the star appear cooler. As the mass-loss rate falls and the wind density decreases, we are able to see deeper into the wind, making the star’s effective temperature appear to increase.

Were the star’s mass-loss rate to decrease further, the star would continue to evolve blueward at constant bolometric luminosity. It is then logical to connect IRC +10420 with the B[e] supergiants (sgB[e]), which occupy the same luminosity range on the HR diagram and whose hybrid spectral characteristics are understood to result from highly axisymmetric outflows (Zickgraf et al. 1986). These stars are often thought of as preceding the RSG phase (e.g., Smith et al. 2004), a reasonable hypothesis given their large H abundances (inferred from their strong Balmer line emission), presumably high rotation rates (inferred from their wind axisymmetry), and lack of circumstellar nebulae. Such stars could potentially shed their angular momentum and spin down on passing through the violent mass-losing RSG/YHG phases, leading the wind geometry to approach spherical symmetry. However, the data we present here show that IRC +10420 still has significant residual wind axisymmetry even after its recent outbursts. Combined with its continued blueward evolution, it cannot now be discounted that IRC +10420 is evolving toward a sgB[e]-like phase.

4. SUMMARY AND CONCLUSIONS

This paper presents the first IFU spectroscopy of the nebula around the transitional massive star IRC +10420. The key observational results of this work can be summarized as follows:

1. DIBs are strikingly uniform across the field, such that they cancel out perfectly when the total spectrum is normalized by the mean nebular spectrum. This is consistent with negligible circumstellar extinction toward the central star, as suggested by Jones et al. (1993) and Oudmaijer (1998).

2. The continuum-subtracted, PSF-subtracted images of H$\alpha$ and Fe $\pi$ both trace the extended morphology of the reflection nebula as shown in the B-band HST image. This supports the reflection-nebula paradigm of this object, as the star is unlikely to produce enough Lyman photons to ionize material out to the distances of the outer nebula.

3. The H$\alpha$ and Fe $\pi$ lines both show a trend of decreasing equivalent width from southwest to northeast of about 25%, following the long axis of the slightly flattened reflection nebula. This is in contradiction to previous observations of this star by Humphreys et al. (2002). That the behavior of the DIBs is so uniform is strong evidence that the $W_L$ behavior of H$\alpha$ and Fe $\pi$ is real.

4. The velocity maps of the H$\alpha$ and Fe $\pi$ lines appear very different, although both have an axisymmetric geometry aligned roughly with the long axis of the nebula.

5. The images in the light of the Ti $\pi$ emission do not trace the nebula morphology, in contrast to the corresponding H$\alpha$ and Fe $\pi$ images. Indeed, the emission is apparently very close to being unresolved. This is inconsistent with the line emission reflecting off the surrounding nebula. The line at 6680 Å is broader than the one at 6718 Å, possibly due to a blend with He $\lambda$ 6678.

We conclude that the $W_L$ behavior of the H$\alpha$ and Fe $\pi$ lines is evidence for an axisymmetric wind geometry in IRC +10420; and that the centroid shifts of these lines across the field are due to complex line profiles (due to e.g., anisotropic infall or B/R variations), which appear different when viewed from different angles by the surrounding nebula. That this behavior was missed by Humphreys et al. (2002) is likely due to the unfortunate orientation of their slit.

The Ti $\pi$ emission does not show the same behavior as the H$\alpha$ and Fe $\pi$ lines, in that the line image does not trace the morphology of the reflection nebula. It is speculated that this emission may originate at the edge of the nebula, in an analog of Cyg’s strontium filament, which also displays enhanced Ti $\pi$ emission. It is noted that high-resolution spectra of IRC +10420 also show the other trademark Sr filament lines of Fe $\iota$, V $\pi$, and Sr $\pi$.

Finally, we speculate that the present-day axisymmetry we observe in IRC +10420, combined with its continued blueward evolution at constant bolometric luminosity, is evidence that the star is evolving toward the B[e] supergiant phase.

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