THE MORPHOLOGY OF IRC+10420’S CIRCUMSTELLAR EJECTA*

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ABSTRACT

Images of the circumstellar ejecta associated with the post-red supergiant IRC+10420 show a complex ejecta with visual evidence for episodic mass loss. In this paper, we describe the transverse motions of numerous knots, arcs, and condensations in the inner ejecta measured from second epoch Hubble Space Telescope/WFPC2 images. When combined with the radial motions for several of the features, the total space motion and direction of the outflows show that they were ejected at different times, in different directions, and presumably from separate regions on the surface of the star. These discrete structures in the ejecta are kinematically distinct from the general expansion of the nebula and their motions are dominated by their transverse velocities. They are apparently all moving within a few degrees of the plane of the sky. We are thus viewing IRC+10420 nearly pole-on and looking nearly directly down onto its equatorial plane. We also discuss the role of surface activity and magnetic fields on IRC+10420’s recent mass-loss history.

Key words: circumstellar matter – stars: activity – stars: individual (IRC+10420) – stars: winds, outflows – supergiants

1. INTRODUCTION

IRC+10420 is one of the most important stars in the upper H-R diagram for understanding the final stages of massive star evolution. With its high luminosity ($L \sim 5 \times 10^5 L_\odot$) and A–F-type spectrum, it is one of the stars that defines the empirical upper luminosity boundary for evolved stars in the H-R diagram (Humphreys & Davidson 1994). IRC+10420 is also a strong OH maser, one of the warmest known, and one of the brightest 10–20 μm IR sources in the sky with its extraordinary mass-loss rate (3–6 × 10$^{-4}$ $M_\odot$ yr$^{-1}$; Knapp & Morris 1985; Oudmaijer et al. 1996; Humphreys et al. 1997).

It has been variously described in the literature as either a true supergiant (Humphreys et al. 1973; Giguere et al. 1976; Mutel et al. 1979) or a proto-planetary/post-AGB star (Habing et al. 1989; Hrivnak et al. 1989; Bowers & Knapp 1989), depending on distance estimates that ranged from 1.5 to 7 kpc. Jones et al. (1993, Paper I) combined multi-wavelength spectroscopy, photometry, and polarimetry to confirm a large distance of 4–6 kpc and the resulting high luminosity mentioned above. This conclusion was supported by Oudmaijer et al. (1996) who demonstrated from CO data that IRC+10420 has to be much more luminous than the asymptotic giant branch (AGB) limit.

Hubble Space Telescope (HST)/WFPC2 images (Humphreys et al. 1997, Paper II) revealed a complex circumstellar environment with numerous small condensations or knots, ray-like features, and intriguing semi-circular arcs or loops. A few other intermediate-temperature hypergiants such as ρ Cas and H-R 8752 occupy the same region in the H-R diagram, but IRC+10420 is the only one with apparent circumstellar nebulosity (Schuster et al. 2006), making it our best candidate for a star in transition from a red supergiant to an S Dor-type variable (LBV), a Wolf–Rayet star, or a pre-supernova state. IRC+10420 has shown some significant changes during the past century. It brightened by a magnitude or more in the 50 yr prior to 1970 (Gottlieb & Liller 1978, Paper I) and its apparent spectral type changed from a late-F to an A-type supergiant in just the past 30 yr (Oudmaijer et al. 1996; Oudmaijer 1998), although Humphreys et al. (2002), hereafter Paper III, demonstrated that IRC+10420’s wind is optically thick. Consequently, the observed variations in apparent spectral type and inferred temperature are more likely due to changes in its wind and not to interior evolution on such a short timescale.

The HST images of IRC+10420 show no obvious axis of symmetry, although the complex ejecta provide evidence for more than one high mass-loss episode. The outermost reflection arcs at $\sim$5” were ejected about 3000 yr ago, possibly when the star was still a red supergiant, while the very complex structures closer to the star correspond to much more recent asymmetric mass-loss events. Surface photometry of the optical and near-infrared images (Paper II) showed that IRC+10420 experienced a high mass-loss episode during the past 600 yr, shedding about 1 $M_\odot$ with a mass-loss rate $\sim 10^{-4} M_\odot$ yr$^{-1}$. Blöcker et al. (1999) suggested that a high mass-loss episode ended $\sim$ 60–90 yr ago which interestingly corresponds to the apparent onset of its brightening. The numerous arcs, knots, and jet-like structures are suggestive of localized ejection events in seemingly random directions which may be due to large-scale active regions on the star (Paper III).

HST/STIS long-slit spectroscopy of the reflection nebula allowed us to effectively view the star from different directions (Paper III). The extracted spectrum at each location is essentially that of a reflection or scattering nebula. Measurements of the absorption minimum in the strong double-peaked Hα emission profile showed that the reflection nebula is expanding in a spherical outflow at $\sim 60$ km s$^{-1}$. Where a slit crossed one of the semi-circular arcs the velocities deviate from the expansion of the surrounding nebulosity indicating that the arc is a kinematically separate feature. The shape of the Hα emission profile was remarkably uniform throughout the ejecta, contrary to what we would expect from previous models with an equatorial disk (Paper I) or bipolar outflow (Oudmaijer et al. 1994, Paper II). More recent observations from integral-field spectroscopy (Davies et al. 2007) provide additional evidence for a bipolar outflow, although the signature is not strong close to the star. Recent near-infrared interferometry (de Wit et al. 2008)
reveals an elongated emitting region on the milliarcsecond scale about twice the size of the star. However, their results are not conclusive as to whether it is an edge-on disk or bipolar outflow. One possible explanation for the apparent conflicting evidence for the outflow and structure of IRC+10420’s circumstellar ejecta may be due to its orientation with respect to our line of sight. We could be viewing IRC+10420 nearly pole-on.

We have now obtained second epoch planetary camera images of IRC+10420 to measure the transverse motions of the discrete structures in the ejecta. In combination with radial velocities from the previous long-slit spectroscopy, we can determine when the material was ejected, a history of IRC+10420’s episodic mass loss, and the morphology of its ejecta based on direct observations. The orientation and vector motions of these features will be important for understanding the origin of the ejecta and the responsible mass-loss mechanism. In the next section, we describe the observations, data processing, and measurement procedure for the transverse motions. In Section 3, we discuss the motions of the separate arcs and knots. We summarize the results on the geometry of the ejecta and IRC+10420’s mass-loss history in Sections 4 and 5 and conclude with remarks on the role of convective activity and magnetic fields in Section 6.

2. THE HST OBSERVATIONS, DATA PROCESSING, AND MEASUREMENT PROCEDURE

2.1. Observations

HST/WFPC2 images of IRC+10420 were obtained on 1996 April 5 (Epoch 1) and on 2008 March 9 (Epoch 2) with the planetary camera giving a baseline of 11.93 yr. The F467M and F547M filters used in Epoch 1 were repeated in Epoch 2 plus additional images with the F675W and F1042M filters. Because of the wide dynamic range of the nebulosity associated with IRC+10420, a range of exposure times was necessary to sample the complex ejecta. For ease of comparison, similar exposure times were used for 467M and 547M. The complete list of filters, exposure times, and the subsequently combined images are given in Table 1. A number of images were taken using the dither mode of the HST. This allows images with matching filters and exposure times to be taken with a 2.5 or 5 pixel offset, which helps identify bad pixels on the chip as well as giving better image detail in the final combined images. The dithered images are noted in Table 1.

Both sets of data were reduced in tandem, using IRAF packages, to assure consistency. We used routines in the HST Dither Handbook (Koekemoer et al. 2002) for a diffuse source imaged with the PC2. Cosmic rays were removed with the task precor and the shift between images in the same epoch were measured with crossdriz and shiftfind. Image masks were created from the bad pixel information from HST and from the images themselves. The final images were created using these masks and the shifts to drizzle the images together. The images were then subsampled by a factor of 2 for a final resolution of 0′02275 pixel$^{-1}$. Images from the same epoch were then aligned and combined. With this resolution at a distance of 5 kpc and 11.9 yr baseline, we expect to be able to measure motions as small as $\sim15$ km s$^{-1}$.

The next step was to remove the point-spread function (PSF). We followed the procedure described in Paper II. We used TinyTIM to create simulated HST specific PSFs to match the WFPC2 observations. However, TinyTIM has several limitations that affect its application to IRC+10420. To produce an accurate PSF for the PC chip, the PSF was subsampled by two, but this decreased the size of the PSF which was already too small for IRC+10420. For IRC+10420 an input size of 18′′ is needed. Furthermore, the TinyTIM PSF is color dependent with a maximum color of 1.6 mag. IRC+10420 is highly reddened by interstellar extinction ($B−V$ color of 2.7 mag); consequently, we adjusted the color table to match the spectral energy distribution of IRC+10420 as closely as possible. The TinyTIM PSFs were then smoothed to match the images. The IRAF task lucy was used to deconvolve the images. Even with the reddened PSF, matching and removing the diffraction spikes for IRC+10420 were only partially successful. When the bright central area was fully subtracted, the diffraction spikes in the extended nebulosity were oversubtracted, creating artifacts. These were easy to recognize because the artifacts were aligned with the diffraction spikes, which were not aligned between the two epochs. To avoid creating artifacts we reduced the number of iterations to 10. To more accurately remove the diffraction spikes in the regions of the knots and arcs we would be measuring, we undersubtracted the innermost region. In the 547M long exposure combinations (547l1 and 547l2), this central area was completely saturated. It was replaced with the center of the corresponding short image (547s1 and 547s2 respectively) and scaled to match the long exposure time to simulate the correct profile for the deconvolution routine to remove the diffraction spikes. A precision alignment

| Date       | Filter | Exposure Times (s) | Combined Images        |
|------------|--------|--------------------|------------------------|
| 1996 Apr 5 | F467M  | 12 s, 30 s × 2, 140 s × 2 | F467s1 (72 s), F467l1 (280 s) |
| (Epoch 1)  | F547M  | 0.5 s, 3 s, 10 s, 40 s, 140 s × 2$^a$ | F547s1 (13.5 s), F547l1 (320 s)$^b$ |
| 2008 Mar 9 | F467M  | 12 s, 30 s × 2, 140 s × 2 | F467s2 (72 s), F467l2 (280 s) |
| (Epoch 2)  | F547M  | 0.5 s, 3 s, 10 s × 2, 40 s, 300 s | F547s2 (23.5 s), F547l2 (340 s)$^c$ |
| F675W      | 0.5 s, 5 s, 30 s × 3, 600 s | F675s (5.5 s), F675I (90 s) |
| F1042M     | 0.5 s, 5 s, 30 s, 100 s | F1042s (5.5 s), F1042I (130 s) |

Notes. All of the images where two or more exposures were taken in the same epoch with the same time were taken using the HST dither technique (except as noted above). The images were offset by 2.5 pixels (short exposures) or 5 pixels (long exposures).

$^a$ The 140 s exposures here were not dithered; see Section 2.1.

$^b$ Filter 547 did not have matching times between the two epochs, so the short and long combined exposures are not the same times between epochs.

$^c$ The 300 s image was combined with the short 40 s image to help remove cosmic rays. The images from Epoch 1 were combined to match the total exposure time as closely as possible for both the short and long exposures.
was then done with the aid of field stars on the edges of the images.

2.2. Measurement Procedure

We combined the multiple $F_{467}M$ and $F_{547}M$ exposures at each epoch into a short (s) and a long (l) exposure for measurement. The combined short and long images in each filter pair were then blinked using DS9 to identify features common to both epochs. Not all of the features were equally visible in both filters and in both epochs. The images could not simply be cross-correlated due to the non-uniform background and the residuals from the PSF subtraction. Each individual knot, condensation, or arc would have required its own cross-correlation which would have been difficult with the variable background. We therefore blinked the aligned images to find observable motion. The center point and position angle of each feature were then measured relative to the central star. This procedure was repeated for each filter combination in which the feature was present. With two filters, short and long, there were four possible combinations. We then repeated these measurements three times, cycling through the four filter combinations in a different order with each set separated by several days to avoid measurement bias. Because of the complications described above with the PSF subtraction we avoided measuring any features near the residual diffraction spikes and within a radius of $\sim0\farcs33$ from the star to avoid confusion with the deconvolution of the star. The diffraction spikes were rotated by $\sim16^\circ$ between the two epochs, so we can be confident that none of the features we measured are associated with them.

The positional offsets in $x$ and $y$ between the two epochs were then determined for each feature. The angular offsets with the number of measurements are given in Table A1. In the following analysis and discussion, we use our preferred distance of 5 kpc (see Paper I). In Table 2, we give the projected radial distance and the position angle relative to the star in the plane of the sky for each measured feature with its corresponding mean transverse velocity, at the adopted distance of 5 kpc, and its direction of motion ($\phi$) with their mean errors. Figure 1 shows a short exposure image ($547s_1$) of IRC+10420 with the outlines of the general regions discussed in this paper. The complex inner two arcsec regions are shown in Figures 2(a) and 2(b) with individual knots and condensations identified. Figure 3 shows an enlargement of a section of one of the semi-circular arcs to illustrate the offset between epochs 1 and 2.

The outer SE feature (see Figure 1) was the one exception to the measurement procedure described above. This large, diffuse feature has no well-defined bright center or condensation, so we used cross-correlation to determine the offset. This worked for this filamentary feature because it is far from the central star and the diffraction spikes, with no significant background. It also has a distinct “V” shape that is easily identifiable between epochs and can be matched using cross-correlation. This was done twice with different sized regions ($\sim1\farcs5$ and $\sim2\farcs5$) around the feature to verify the cross-correlation. No other features in the outer regions are prominent enough to be measured this way.

3. THE KINEMATICS OF THE EJECTA

Radial velocities, measured from the absorption minimum in the very strong H$\alpha$ line, are available for numerous positions along two separate slits from the long-slit spectra obtained with HST/STIS in 1999 (Paper III). The slits cross several of the brighter knots and arcs near the star, including one of the semi-circular arcs. The observed spectrum is that of an expanding reflection nebula and the apparent Doppler velocity at each reflective condensation is due to the velocity of the star when
it is observed directly, the expansion velocity of the nebula, and the relative velocity component along our line of sight of the condensation. Figure 9 in Paper III shows the measured Doppler velocity increasing with increasing distance from the star. The relation between the measured velocities and the three-dimensional position can be fit by an expansion of 50 km s$^{-1}$ (Paper III), consistent with the outflow velocities from the CO and OH observations and the double-peaked hydrogen and CaII emission. Adopting this model for the expansion of the nebula we can estimate the relative motions of the knots and arcs along the line of sight. The relative radial component is combined with the measured transverse velocity to determine the total space motion and the combined direction of motion relative to the plane of the sky for individual knots. The results are included in Table 3. In the subsequent discussions, all of the expansion ages or time since ejection are determined assuming a constant speed since ejection. For those objects with only a transverse motion, the expansion age is an upper limit. The resulting ages and

| Feature ID | Radial Distance (arcsec) | Position Angle (deg) | $V_{\text{trans}}$ (km s$^{-1}$) | $\phi$ (deg) | Expansion Age (yr) |
|------------|--------------------------|----------------------|---------------------------------|--------------|-------------------|
| SE Jet(1), Knot A$^a$ | 0.57 | 122 ± 3 | 17 ± 10 | 127 ± 10 | 800$^{+1100}_{-100}$ |
| SE Jet(1), Knot B | 0.69 | 126 ± 3 | 27 ± 9 | 140 ± 12 | 600$^{+300}_{-150}$ |
| SE Jet(2), Knot A$^a$ | 0.38 | 175 ± 3 | 126 ± 6 | 144 ± 3 | 83$^{+3}_{-1}$ |
| SE Knot A | 0.57 | 136 ± 3 | 89 ± 7 | 180 ± 3 | 160$^{+12}_{-10}$ |
| SE Knot B | 1.02 | 152 ± 2 | 42 ± 14 | 80 ± 16 | 600$^{+1100}_{-50}$ |
| SE Knot C | 1.17 | 137 ± 3 | 118 ± 20 | 11 ± 3 | 230$^{+50}_{-15}$ |
| SE Knot D | 1.35 | 138 ± 3 | 60 ± 12 | 104 ± 8 | 550$^{+150}_{-50}$ |
| SE Knot E | 1.58 | 141 ± 2 | 54 ± 5 | −139 ± 2 | 700$^{+70}_{-70}$ |
| SE Knot F | 1.25 | 149 ± 2 | 69 ± 13 | 137 ± 6 | 450$^{+1100}_{-70}$ |
| SE Knot G | 1.39 | 148 ± 2 | 98 ± 7 | 161 ± 2 | 350$^{+20}_{-25}$ |
| SE Outer Knot | 4.01 | 143 ± 2 | 49 ± 10 | 122 ± 5 | 2000$^{+1500}_{-230}$ |
| SW Jet, Knot B$^a$ | 0.54 | −173 ± 2 | 218 ± 9 | −165 ± 3 | 70$^{+5}_{-5}$ |
| SW Square, Knot A | 1.06 | −125 ± 2 | 131 ± 5 | 133 ± 3 | 190$^{+10}_{-10}$ |
| SW Square, Knot B | 1.07 | −137 ± 3 | 128 ± 10 | −167 ± 3 | 200$^{+20}_{-15}$ |
| SW Square, Knot C$^a$ | 1.24 | −136 ± 2 | 96 ± 21 | −160 ± 8 | 320$^{+300}_{-50}$ |
| SW Square, Knot D | 1.30 | −132 ± 2 | 89 ± 15 | −174 ± 6 | 360$^{+150}_{-50}$ |
| SW Knot A | 1.36 | −146 ± 3 | 41 ± 6 | −80 ± 4 | 800$^{+1500}_{-100}$ |
| SW Triangle, Knot A | 1.18 | −159 ± 2 | 214 ± 22 | −145 ± 6 | 140$^{+20}_{-15}$ |
| SW Triangle, Knot B | 1.26 | −165 ± 2 | 15 ± 9 | −6 ± 18 | b |
| SW Triangle, Knot C | 1.46 | −155 ± 3 | 50 ± 8 | −109 ± 8 | 700$^{+125}_{-100}$ |
| SW Fan, Knot A | 1.99 | −180 ± 3 | 104 ± 31 | −174 ± 16 | 470$^{+200}_{-100}$ |
| SW Fan, Knot B$^a$ | 1.89 | −135 ± 2 | 103 ± 25 | −149 ± 10 | 450$^{+140}_{-100}$ |
| E Jet, Knot B | 0.66 | 85 ± 2 | 165 ± 17 | 61 ± 5 | 92$^{+45}_{-10}$ |
| E Jet, Knot C | 0.82 | 89 ± 2 | 136 ± 5 | 161 ± 4 | 150$^{+130}_{-10}$ |
| NE Knot G | 0.85 | 16 ± 2 | 94 ± 16 | −148 ± 6 | 200$^{+30}_{-5}$ |
| Arc 1, Knot A | 1.32 | 67 ± 2 | 50 ± 7 | −180 ± 6 | 650$^{+1200}_{-10}$ |
| Arc 1, Knot B$^a$ | 1.33 | 57 ± 2 | 116 ± 5 | −173 ± 3 | 270$^{+10}_{-10}$ |
| Arc 1, Knot C$^a$ | 1.64 | 57 ± 2 | 108 ± 20 | 81 ± 4 | 380$^{+90}_{-100}$ |
| Arc 1, Knot D | 1.71 | 65 ± 2 | 130 ± 5 | 158 ± 2 | 300$^{+150}_{-40}$ |
| Arc 1, Knot E | 1.68 | 67 ± 2 | 69 ± 14 | 139 ± 7 | 570$^{+150}_{-100}$ |
| Arc 1, Knot G$^a$ | 1.50 | 73 ± 2 | 107 ± 13 | 116 ± 3 | 330$^{+50}_{-100}$ |
| Arc 2, Knot A | 1.50 | 78 ± 2 | 110 ± 25 | 166 ± 11 | 330$^{+80}_{-100}$ |
| Arc 2, Knot B | 1.84 | 81 ± 2 | 62 ± 21 | −155 ± 13 | 700$^{+300}_{-20}$ |
| Arc 2, Knot C | 1.98 | 84 ± 2 | 87 ± 15 | 141 ± 6 | 550$^{+100}_{-10}$ |
| Arc 2, Knot D | 1.87 | 89 ± 2 | 88 ± 10 | 150 ± 6 | 500$^{+90}_{-100}$ |
| Arc 2, Knot E | 1.59 | 86 ± 2 | 119 ± 25 | 134 ± 8 | 300$^{+130}_{-100}$ |
| Arc 2, Knot F$^a$ | 1.64 | 73 ± 2 | 97 ± 13 | 148 ± 9 | 400$^{+100}_{-70}$ |
| Arc 3, Knot A$^c$ | 1.66 | 104 ± 2 | 23 ± 17 | −86 ± 3 | 1700$^{+1000}_{-300}$ |
| Arc 3, Knot B | 1.77 | 114 ± 2 | 102 ± 13 | 158 ± 6 | 420$^{+150}_{-50}$ |
| Arc 3, Knot C | 1.51 | 117 ± 2 | 199 ± 14 | 111 ± 3 | 200$^{+20}_{-15}$ |

Notes.

$^a$ These features also have radial velocities and are listed in Table 3.

$^b$ The transverse velocity is too small to find a meaningful expansion age.

$^c$ This knot is very close to a diffraction spike which causes the high error to the velocity and age.
are identified and listed separately to differentiate them from the ages found from the total velocity.

The results for the individual features identified in Figures 1 and 2 are summarized in Tables 2 and 3. In the following subsections, we discuss a few of the major features, the east jet, the SW fan, the SW square, and the semi-circular arcs.

3.1. The East Jet

The east jet (Figure 2(b)) is one of the more visible features in the ejecta. It appears to be a row of several knots aligned almost directly east of the star. In the first epoch image the knots are quite close to a diffraction spike, so the innermost knots closest to the star were not measurable between the two epochs. Knots B and C have transverse velocities of 165 km s$^{-1}$ and 136 km s$^{-1}$. Their respective times since ejection are 100 and 150 yr, indicating that they are from a common recent ejection event, similar to SE Jet(2) Knot A. Knot C also has a small radial motion ($-5.9$ km s$^{-1}$). It is thus moving at 136 km s$^{-1}$ essentially in the plane of the sky at an angle of only $2.5^\circ$ toward us.

3.2. The Southwest Fan

The scalloped or rippled pattern to the SW of the star that we call the fan is very prominent in the images of IRC+10420 (see Figure 1). However, the complexity of this region makes it hard to compare the diffuse condensations between the two epochs with a high degree of confidence. Knots A and B (Figure 2(a)) are sufficiently distinct and bright enough that they can be identified in the images from both epochs. Knots A and B have essentially the same transverse velocities ($\approx$100 km s$^{-1}$) and a corresponding expansion age of 450–470 yr. Both knots move nearly radially away from the star. Knot B also has a radial motion of $-15.3$ km s$^{-1}$ yielding a total velocity of 104 km s$^{-1}$ and an ejection time of 450 yr ago. The fact that these knots have such similar properties, despite being separated by $1^\prime.5$, suggests that the fan is a physically distinct feature from a single mass-loss event.

3.3. The Southwest Square and The Southwest Jet

The southwest square is a grouping of four knots $1^\prime-1.3$ from the star (Figure 2(a)) with position angles from $-125^\circ$ to $-137^\circ$. Knots B, C, and D have similar velocities (89–107 km s$^{-1}$) as well as similar directions of motion (from $-160^\circ$ to $-174^\circ$).
which are more or less radially away from the star. Their expansion ages from their transverse motions range from 250 to 360 yr. Knot C also has a radial velocity of $-19.5$ km s$^{-1}$, which gives a total velocity of 98 km s$^{-1}$ and an expansion age of 320 yr. These results suggest a common ejection event for these three knots.

The southwest jet only has one measurable knot. It moves radially outward at 218 km s$^{-1}$ with an expansion age of only 70 yr. Its small associated radial motion of $-5.6$ km s$^{-1}$ does not alter its space motion or time since ejection.

### 3.4. The Semi-circular Arcs

Three very intriguing nearly circular arcs can be easily seen to the east of the star (Figure 1). The arcs appear to be made up of several small knots, identified in Figure 4, that form the larger arcs or loops. Given their appearance, it is possible that these knots may have been part of three initially much more compact features, and the nearly circular arcs we observe now are actually expanding bubbles or loops.

We initially measured the motions of the individual knots with respect to the star as we did for the other condensations discussed in this section (Table 2). The six knots in Arc 1 have a mean transverse velocity of 97 km s$^{-1}$ and a corresponding mean time since ejection of about 400 yr. Given its location, Knot A may be a separate condensation simply projected onto Arc 1. Excluding it gives 103 km s$^{-1}$ and 370 yr. Radial velocities are available for three of the knots (Table 3) giving a mean total velocity of 111 km s$^{-1}$ and an expansion age of 320 yr. We note that the three knots are consistent with a mean orientation that places them essentially in the plane of the sky, although there may be a slight tilt to the arc. Knot A in Arc 2 appears to be on the inside edge of the arc, is difficult to measure, and gives an indefinite result. Excluding Knot A, the other five knots give a mean transverse velocity of 91 km s$^{-1}$ and a corresponding mean time since ejection of 500 yr. Knot F has an associated radial velocity and a corresponding expansion age of 400 yr. Arc 3 is the least well defined in the images and we were able to measure only three knots. Knots B and C in Arc 3 give consistent results with a mean transverse velocity of 150 km s$^{-1}$ and an expansion age of $\approx 300$ yr.

The arcs are all about the same radial distance from the star, and the results for the individual knots suggest that they may all have been ejected at about the same time, 300–400 yr ago.

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### Table 3

| Feature         | $V_{\text{Trans}}$ (km s$^{-1}$) | $V_R$ (km s$^{-1}$) | $V_{\text{Total}}$ (km s$^{-1}$) | $\theta$ (deg) | Expansion Age (yr) |
|-----------------|----------------------------------|---------------------|-----------------------------------|----------------|---------------------|
| East Jet, Knot C| 136                              | $-5.9$              | 136 $\pm$ 10                      | $-2.5$ $\pm$ 2 | $150^{+12}_{-10}$   |
| SE Jet (1), Knot A| 18                              | $-3.6$              | 17 $\pm$ 12                       | $-12$ $\pm$ 0.6 | $800^{+3000}_{-300}$|
| SE Jet (2), Knot A| 126                             | $-3.8$              | 126 $\pm$ 11                      | $-1.7$ $\pm$ 1.4 | $80^{+15}_{-7}$     |
| SW Jet, Knot B   | 218                              | $-5.6$              | 218 $\pm$ 12                      | $-1.5$ $\pm$ 1.3 | $70^{+15}_{-10}$    |
| SW Sq, Knot C    | 96                               | $-19.5$             | 98 $\pm$ 21                       | $-11.5$ $\pm$ 4 | $320^{+90}_{-60}$   |
| SW Fan, Knot B   | 103                              | $-15.3$             | 105 $\pm$ 25                      | $-8.4$ $\pm$ 3.8 | $450^{+140}_{-90}$  |
| Arc 1, Knot B    | 116                              | 16.3                | 117 $\pm$ 16                      | $8$ $\pm$ 3     | $270^{+40}_{-50}$   |
| Arc 1, Knot C    | 108                              | 3.3                 | 108 $\pm$ 19                      | $1.8$ $\pm$ 1.2  | $380^{+80}_{-60}$   |
| Arc 1, Knot G    | 107                              | $-6.5$              | 107 $\pm$ 13                      | $-3.5$ $\pm$ 2.5 | $330^{+50}_{-40}$   |
| Arc 2, Knot F    | 97                               | $-9$                | 98 $\pm$ 13                       | $-5.3$ $\pm$ 3.2 | $400^{+50}_{-40}$   |

**Notes.** For transverse velocity errors see Table 2. Errors in $V_R$ are assumed to be on the order of 3 km s$^{-1}$ for calculation purposes. They are much less than the transverse velocity errors.

*From Table 2.*

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To investigate whether the arcs are expanding bubbles, we examined the motions of the knots with respect to the center of their respective arcs. We first found the center of each arc by fitting an ellipse to the positions of the knots in DS9. We experimented with different ellipticities and adopted the best fit to the measured positions of the knots that also best mapped the inter-knot diffuse nebulosity. This was done independently for each epoch. The percentage difference between the positions of the knots and the elliptical fit was used to determine the quality of the fit. The center of the best-fit ellipse was then adopted as center of each arc. The corresponding transverse motion between the two epochs is summarized in Table 4.

While we were able to determine a best fit, the adopted error for the velocity of each arc center is from the range in the transverse velocity derived from the different fits.

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1. In Arc 2, Knot A was not used to determine the best-fit position and was not included in the percentage difference calculations.
Radial motions are available for three knots in Arc 1. Consequently, we were able to solve for the velocity of the arc center assuming that the velocities of the knots, relative to the star, depend on the radial velocity of the center and their $x$ and $y$ positions relative to the arc center. The resulting radial velocity for the center of Arc 1 is essentially 0 km s$^{-1}$, from both Epochs 1 and 2, giving a total space motion of 51 km s$^{-1}$ and a time since ejection of 700 yr.

With this information for Arc 1 we then determined the transverse motion of the individual knots relative to the arc center and for knots B, C, and G, with radial velocities, their total motions and orientation or tilt relative to the arc center. These results are summarized in Tables 5 and 6. The results confirm that Arc 1 is slightly tilted with respect to our line of sight. We also find that the expansion age or time for the arc of $\sim 100$ yr is significantly less than the time since ejection from the star whether we use the $700 \pm 100$ yr or the $370 \pm 200$ yr.

The transverse motion for the Arc 2 center gives a time since ejection of $370^{+200}_{-100}$ yr. Only Knot F in Arc 2 has a measured radial velocity; consequently, there is no radial velocity estimate for the arc center. The transverse motions for the individual knots give an average expansion time for the arc of $\sim 200$ yr. Although

### Table 4

| Arc   | Position Angle (deg) | $V_{\text{Trans}}$ (km s$^{-1}$) | $\phi$ (deg) | Expansion Age (yr)$^a$ | $V_{\text{R}}$ (km s$^{-1}$) | $V_{\text{Total}}$ (km s$^{-1}$) | $\theta$ (deg) |
|-------|----------------------|----------------------------------|--------------|------------------------|-----------------------------|-------------------------------|----------------|
| Arc 1 | 64 ± 5               | 51 ± 30$^b$                      | 153 ± 10     | 700$^{+1000}_{-400}$   | −0.4                        | 51 ± 30                      | −0.4 ± 0.8                |
| Arc 2 | 84 ± 5               | 107 ± 40$^b$                     | 155 ± 8      | 370$^{+200}_{-100}$    | ...                         | ...                          | ...                        |
| Arc 3 | 111 ± 5              | 140 ± 50$^b$                     | 121 ± 10     | 300$^{+200}_{-100}$    | ...                         | ...                          | ...                        |

**Notes.** Values listed for the arcs are for the best fits only.

$^a$ This expansion age is for the center of the arc relative to the star and not for the individual knots.

$^b$ The errors are from the spread in velocities found with the different fits to each arc.

### Table 5

The Position, Transverse Velocity, and Direction of Motion Relative to the Arc Center

| Feature ID | Radial Distance (arcsec) | Position Angle (deg) | $V_{\text{Trans}}$ (km s$^{-1}$) | $\phi$ (deg) | Expansion Age (yr) $^a$ |
|------------|--------------------------|----------------------|----------------------------------|--------------|------------------------|
| Arc 1, Knot A | 0.19                     | −132 ± 2            | 23 ± 15                          | −97 ± 4      | 200$^{+100}_{-100}$    |
| Arc 1, Knot B | 0.23                     | −66 ± 2             | 79 ± 15                          | −173 ± 2     | 70$^{+100}_{-50}$     |
| Arc 1, Knot C | 0.27                     | −4 ± 2              | 99 ± 15                          | 51 ± 3       | 65$^{+100}_{-50}$     |
| Arc 1, Knot D | 0.22                     | 69 ± 2              | 44 ± 15                          | −20 ± 3      | 120$^{+450}_{-70}$    |
| Arc 1, Knot E | 0.19                     | 88 ± 2              | 24 ± 18                          | 107 ± 6      | 190$^{+900}_{-100}$   |
| Arc 1, Knot G | 0.20                     | 169 ± 3             | 74 ± 15                          | 90 ± 3       | 65$^{+100}_{-50}$     |
| Arc 2, Knot A | 0.25                     | −50 ± 3             | 21 ± 13                          | −62 ± 9      | 280$^{+100}_{-100}$   |
| Arc 2, Knot B | 0.24                     | 57 ± 3              | 83 ± 21                          | −60 ± 2      | 70$^{+150}_{-40}$    |
| Arc 2, Knot C | 0.31                     | 84 ± 3              | 31 ± 15                          | 18 ± 4       | 235$^{+100}_{-100}$   |
| Arc 2, Knot D | 0.21                     | 122 ± 3             | 20 ± 12                          | −5 ± 26      | 250$^{+100}_{-100}$   |
| Arc 2, Knot E | 0.25                     | −165 ± 3            | 42 ± 15                          | −71 ± 13     | 150$^{+100}_{-100}$   |
| Arc 2, Knot F | 0.36                     | −17 ± 15            | 21 ± 12                          | −27 ± 15     | 400$^{+400}_{-100}$   |
| Arc 3, Knot A | 0.24                     | 33 ± 3              | 160 ± 15                         | −63 ± 5      | 36$^{+50}_{-20}$     |
| Arc 3, Knot B | 0.13                     | 144 ± 3             | 85 ± 15                          | 106 ± 6      | 37$^{+60}_{-30}$     |
| Arc 3, Knot C | 0.21                     | −130 ± 3            | 68 ± 15                          | 90 ± 5       | 74$^{+200}_{-40}$    |

**Notes.**

$^a$ These are the radial velocities relative to the value at the arc center (see Section 3.4). Negative values indicate the knot was moving faster than the arc center and coming toward us with respect to the arc center.

$^b$ These errors are based solely on the measurement values and do not include errors from the measurement of the arc center.

### Table 6

The Three-dimensional Motion of Arc 1 With Respect to the Arc Center

| Feature ID | Position Angle (deg) | $V_{\text{Trans}}$ (km s$^{-1}$) | $\phi$ (deg) | $V_{\text{R}}$ (km s$^{-1}$) | $\theta$ (deg) | $V_{\text{Total}}$ (km s$^{-1}$) |
|------------|----------------------|----------------------------------|--------------|-----------------------------|---------------|-------------------------------|
| Arc 1, Knot A | −132 ± 2             | 23 ± 10                          | −97 ± 7      | ...                         | ...           | ≥23                           |
| Arc 1, Knot B | −66 ± 2              | 79 ± 11                          | −173 ± 7     | 16.7                        | 12 ± 3        | 81 ± 13                       |
| Arc 1, Knot C | −4 ± 2               | 99 ± 13                          | 51 ± 7       | 3.7                         | 2.1 ± 3       | 99 ± 14                       |
| Arc 1, Knot D | 69 ± 3               | 44 ± 12                          | −20 ± 7      | ...                         | ...           | ≥44                           |
| Arc 1, Knot E | 88 ± 2               | 24 ± 11                          | 107 ± 7      | ...                         | ...           | ≥24                           |
| Arc 1, Knot G | 169 ± 3              | 74 ± 12                          | 90 ± 7       | −6.1                        | −4.8 ± 3      | 74 ± 14                       |

**Notes.**

$^a$ These are the radial velocities relative to the value at the arc center (see Section 3.4). Negative values indicate the knot was moving faster than the arc center and coming toward us with respect to the arc center.

$^b$ These errors are based solely on the measurement values and do not include errors from the measurement of the arc center.
There is a large spread in the results for the knots (Table 5), the results for the expansion of the arc itself and the ejection times for the knots are consistent within the measurement uncertainties.

Arc 3 has an expansion age with respect to the star of $300^{+200}_{-100}$ yr from its transverse motion. No radial velocity information is available. The expansion time of 50 yr for the knots relative to the arc center (Table 5) is significantly less than the time since ejection from the star, although motions are available for only three knots. Except for Knot A, the expansion times relative to the star from the transverse motion of the other two knots (Table 2) are consistent with the result for the arc center.

For the arcs there is thus evidence that the expansion time for the arc itself is less than the time since its ejection from the star. The possible causes of these different expansion times are discussed in Section 5.

In summary, the knots, arcs, etc., are kinematically distinct from the general expansion of the ejecta. The mean total space motion of the 10 knots in Table 3 is $113 \pm 14$ km s$^{-1}$ compared to the $40–60$ km s$^{-1}$ velocity of expansion inferred from the double-peaked profiles of the hydrogen and Ca II emission and the maser emission. Their mean space motion is due almost entirely to the mean transverse velocity of $112 \pm 15$ km s$^{-1}$ compared to only $5 \pm 3$ km s$^{-1}$ for the radial motion. Similarly, the mean transverse velocity for the remaining features in Table 2 is $89 \pm 9$ km s$^{-1}$. In almost all cases with a radial velocity, the transverse motions are significantly larger than the radial component. The motions of the discrete features are thus dominated by their transverse motions.

4. GEOMETRY OF THE EJECTA

The morphology of IRC+10420's circumstellar ejecta has eluded previous studies. While the outer rings are consistent with a basically spherical outflow from several thousand years ago perhaps when the star was in a different evolutionary state as a red supergiant, the inner ejecta is very complex and indicative of localized ejection events. Suggestions for the orientation and geometry of the ejecta have ranged from an equatorial disk viewed at an angle to our line of sight (Paper I), a bipolar outflow (Oudmaijer et al. 1994, Paper II, Davies et al. 2007) to an essentially spherical outflow (Paper III). Similarly, the various interpretations based on the strong OH maser emission include a spherical outflow (Bowers 1984), a bipolar outflow with a disk-like structure viewed edge-on, and a weakly bipolar, slightly oblate outflow with clumping (Nedoluha & Bowers 1992).

Our results for the total space motions and resulting orientation for several of the discrete knots and condensations (Table 3) interestingly show that while they have a range of ejection velocities and expansion ages they are all moving very close to the plane of the sky or toward us by at most about $12^\circ$. With an optical thickness greater than one for IRC+10420's inner ejecta (Paper II), it is not surprising that we do not find any features moving away from us. The similar orientation of most of these features, at different position angles and ejected at different times over several hundred years, suggests that we are viewing IRC+10420 nearly pole-on and therefore, looking nearly directly down onto its equatorial plane. The SW fan, which extends over an arc covering approximately $70^\circ$ projected onto the sky, is a likely candidate to represent the equatorial plane which would then be tilted by only about $8^\circ$ out of the plane of the sky with the southwest side of the ejecta toward us. The other features, the various knots and the semi-circular arcs, would then all lie within $\approx 10^\circ$ of the equatorial plane. Furthermore as noted above, the motions of the various knots, etc., are dominated by their transverse velocities. They have little radial motion, supporting the interpretation that we are viewing these features essentially face-on.

Davies et al. (2007) have presented evidence in support of a bipolar outflow based on the velocities of the reflected Hα and Fe II emission across the nebula and argue for a preferred axis of symmetry at $\approx 45^\circ$ on the basis of the optical and infrared images. The Hα and Fe II emission however show different kinematic patterns. The Fe II does not show a clear bipolar pattern; it has radial gradient with lower velocities near the center and higher in the outer parts. Hα shows the strongest evidence for bipolarity with lower velocities to the SW and higher velocities to the NE with a typical velocity difference of $\approx 10$ km s$^{-1}$ within the inner region; the strongest evidence for an outflow is beyond the inner $2''$.

We looked for any evidence for an axis of symmetry in the motion of the knots especially between the SW and SE/NE quadrants of the nebula.\footnote{The semi-circular arcs were not included because of possible expansion.} For those few knots with radial motions, we find a small difference of $12$ km s$^{-1}$ with the SW quadrant having a larger component of motion toward us. Given the apparent orientation of the ejecta, this is not surprising and may be due as much to the tilt of the SW side toward our line of sight as to a bipolar outflow. Given the nearly pole-on geometry of the inner ejecta, the motions and orientation of the various arcs and knots within about $2''$ do not provide any direct information on an axis of symmetry or bipolar outflow, and the apparent velocity difference in the Hα emission with position in the inner nebula may also be due as much to its geometry as to an actual bipolar outflow.

In our previous papers on the extreme red supergiant VY CMa (Smith et al. 2001; Humphreys et al. 2005, 2007; Smith 2004), we have emphasized the presence of prominent arcs, knots, and large loop-like structures in its very visible ejecta, all evidence for localized ejections which we have suggested are due to large-scale surface activity and magnetic fields. There are both similarities and important differences between the circumstellar environments of VY CMa and IRC+10420, although we are viewing them from different perspectives.\footnote{VY CMa may be tilted by $\approx 15^\circ$ to the line of sight.} IRC+10420's ejecta is apparently concentrated to the equatorial plane and it does not show the large prominence-like loops seen in VY CMa; however, the semi-circular arcs may be evidence for related structures.

5. DISCUSSION: MASS-LOSS HISTORY

The circumstellar ejecta of IRC+10420 separates into the outer approximately spherical shells $5''–6''$ from the star and the complex inner ejecta within $2''$ of the star. Adopting the nominal expansion velocity of $\approx 50–60$ km s$^{-1}$ the outer shells were ejected about 3000 yr ago. Our transverse motion for the outer nebulous about $4''$ away confirms an expansion age of $\approx 2000$ yr. There is also evidence for more distant associated ejecta $8''–9''$ away (Figure 5). This visual nebulous very
likely corresponds to the distant arc reported by Kastner & Weintraub (1995) from coronagraphic imaging in the near-infrared. Assuming that this material was expelled with a similar velocity, then it would have been ejected 4000–5000 yr ago. These outer shells are similar to the shells or ejecta associated with many post-AGB stars and very likely result from pulsational mass loss as a red supergiant in the case of IRC+10420. In contrast, the inner circumstellar material was apparently ejected at different times and in different directions beginning about 600–800 yr ago up to fairly recently ending perhaps less than 100 yr ago. This result is consistent with beginning about 600–800 yr ago up to fairly recently ending apparently ejected at different times and in different directions from pulsational mass loss as a red supergiant in the case of IRC+10420. These outer shells are similar to the shells or ejecta from pulsational mass loss as a red supergiant in the case of IRC+10420. This result is consistent with the results for the knots in Arc 1 being internally consistent. As discussed in Section 3.4, the semi-circular arcs may be expanding as well as traveling away from the star. An ejection time of 300–400 yr is consistent within the errors for all three arcs, although it may be as high as 700 yr for Arc 1. The results for Arcs 1 and 3 also indicate expansion times much less than the time since ejection from the star. This could be due to the significant uncertainty in these measurements although the results for the knots in Arc 1 are internally consistent. As discussed in the next section, magnetic fields may play a role in the origin of IRC+10420’s episodic mass loss. They may also provide an explanation for the much shorter measured expansion times for the arcs. The strength of the magnetic field is estimated from the circular polarization of the OH masers on the inside edge of the maser shell at about 7000 AU from the star (Nedoluha & Bowers 1992), the average distance of the arcs (see Figure 6). Suzuki (2007) has demonstrated that it is possible for hot bubbles ejected from red supergiants to last much longer than their cool down times due to extended magnetic field lines from the star which constrain the bubbles of gas as they travel away from the star. While the models do not include stars as warm as IRC+10420, magnetic fields may restrict the expansion of a bubble or loop. Given the apparent tilt of Arc 1, it also seems likely that the arcs are actually expanding loops similar to the much larger structures in the ejecta of VY CMa.

The morphology of IRC+10420’s inner ejecta shows a recent mass-loss history dominated by localized ejection events in random directions and at different times. Mass loss and the winds of cool evolved stars including the AGB stars, red supergiant, and red giants are normally attributed to global pulsation combined with radiation pressure on the dust which further drives the mass loss. These mechanisms can account for relatively uniform essentially spherical ejecta like IRC+10420’s outer shells. But the complex and episodic mass loss evident in the inner regions require a non-uniform mass-loss mechanism such as large-scale surface activity. There is now an increasing number of observations of “starspots,” large surface asymmetries, and outflows associated with red supergiants, giants, and AGB stars (Tuthill, Haniff & Baldwin 1997; Monnier et al. 2004; Kiss et al. 2009) consistent with a convective origin. Non-radial pulsations may be an alternative but are not consistent with the narrow loop-like structures observed, for example, in the ejecta of VY CMa. Furthermore, magnetic fields associated with the maser emission are now confirmed in the ejecta of several of these stars including the strong OH/IR sources, VX Sgr, S Per, NML Cyg, and VY CMa (Vlemmings et al. 2002, 2004).

Magnetic field strengths from \( \approx 1/6 \) to 15 mG have also been reported in the ejecta of IRC+10420 from the observed circular polarization of the OH maser emission (Reid et al. 1979; Cohen et al. 1987; Nedoluha & Bowers 1992). Figure 6 shows the distribution of the various maser sources superimposed on an image of IRC+10420. The inner OH emission at \( \approx 1/5 \) is the location of the circularly polarized emission and is coincident with the inner ejecta. Adopting a conventional extrapolation (\( B \propto r^{-2} \)), a 1 mG field at \( r \approx 5000–7000 \) AU would give \( B \approx 3 \) kG at the stellar surface, high for a global field, and it would also exceed other local energy densities (see Paper III). A field proportional to \( r^{-1} \), however, would give a surface magnetic energy density comparable to the thermal energy density. We also note that in the case of IRC+10420, the knots and arcs appear to be concentrated in the equatorial region. We know

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**Figure 5.** Long exposure red image showing the outermost nebulosity at 8′′–9′′ from the central star.

**Figure 6.** Image 547/l with the peak maser emissions overlaid: SiO (Castro-Carrizo et al. 2001), the inner OH ring (Nedoluha & Bowers 1992), ammonia (Menten & Alcolea 1995), and the outer CO emission (Castro-Carrizo et al. 2007).
that as a star evolves to warmer temperatures the increased
dynamical instability will be enhanced in the equatorial region
as the star’s rotation also increases. Thus for IRC+10420 we may
be observing the combined effects of turbulence/convection and
increased rotation.

The case for the role of convection and magnetic fields on
the mass loss history and mechanism in evolved massive stars is
of course strongest in the red supergiant stage. IRC+10420 is a
probable source of their high mass-loss episodes especially in
their final stages.

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APPENDIX

ANGULAR MEASUREMENTS

The measurements for the individual features in the different
filter combinations with the number of independent measure-
ments are summarized in Table A1.

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