SMOKE SIGNALS FROM IRC+10216. I. MILLIARCSECOND PROPER MOTIONS OF THE DUST

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ABSTRACT

The results of a seven epoch interferometric imaging study, at wavelengths in the near-infrared K band, of the carbon star IRC+10216 are presented. The use of non- and partially redundant aperture masking techniques on the 10 m Keck I telescope has allowed us to produce images of the innermost regions of the circumstellar dust envelope with unprecedented detail. With roughly twice the resolving power of previous work, the complex asymmetric structures reported within the central 0.5 (~20 R\(_\odot\)) have been imaged at the size scale of the stellar disk itself (~50 mas). A prominent dark lane at a position angle of approximately 120\(^\circ\) is suggested to be an optically thick disk or torus of dust which could help to explain IRC+10216's well-known bipolarity at a position angle of ~20\(^\circ\). Observations spanning more than a pulsational cycle (~638 days) have revealed significant temporal evolution of the nebula, including the outward motion of bright knots and clumps. Registering these displacements against the compact bright core, which we tentatively identify as marking the location of the star, has allowed us to determine the apparent angular velocity at a number of points. The magnitudes of the proper motions were found to be in agreement with current estimates of the stellar distance and radial velocity. Higher outflow speeds were found for features with greater separation from the core. This is consistent with acceleration taking place over the region sampled by the measurements; however, alternate interpretations are also presented. Although a number of changes of morphology were found, none were clearly interpreted as the condensation of new dust over the pulsation cycle. Unfortunately, ambiguities associated with the true three-dimensional nature of the nebula weaken a number of our quantitative and qualitative conclusions.

Subject headings: circumstellar matter — infrared: stars — ISM: jets and outflows — stars: AGB and post-AGB — stars: individual (IRC+10216) — stars: mass loss

1. INTRODUCTION

The extreme carbon star IRC+10216 is a classic example of a red giant caught in the act of evolving into a planetary nebula. Its relative proximity, high-infrared luminosity, and abundance of molecules found in its dense outflow has resulted in a barrage of observations by astronomers, working across the spectrum, but particularly in the infrared and millimeter/submillimeter. Despite all this attention, a good model of what is happening in the innermost regions where the stellar outflow is born and accelerated is still sorely lacking.

Numerous studies of molecular lines in the outer envelope (e.g., Bieging & Tafalla 1993) have revealed a spherically expanding outflow, a finding which was beautifully confirmed with deep B- and V-band images of the dust shell in ambient scattered galactic light (Mauron & Huggins 1999). However, this spherical symmetry, a characteristic of most red giant winds, will likely be broken as IRC+10216 evolves into a planetary nebula, most of which are elongated or bipolar (e.g., Zuckerman & Aller 1986). The pronounced asymmetry in the innermost regions of the envelope of IRC+10216 reported by numerous high-resolution imaging experiments (most recently, Weigelt et al. 1997, 1998; Danchi et al. 1998; Haniff & Buscher 1998; Skinner et al. 1998) and also polarization studies (Trammell, Dinerstein, & Goodrich 1994; Kastner & Weintraub 1994) suggests that the onset of this aspherical flow has already begun, probably within the last few hundred years. With a privileged vantage onto such a brief yet important period in the evolution of a low- to intermediate-mass (initial mass ~3-5 M\(_\odot\); Guélin et al. 1995) star, high-resolution observations are crucial in distinguishing among the many competing models for the physical mechanisms underlying the onset of asymmetry in the birth of a planetary nebula.

In this paper, we present a seven epoch diffraction-limited imaging study of the inner dust shell of IRC+10216 in the near-infrared K band. Although some interpretation of the morphology of the images is given, full radiative transfer modeling results are beyond the scope of this report and will be presented in a second paper. Instead, we emphasize here the detection and measurement of the motion of features presumably embedded in the outflow. Although proper motions have been reported for near-infrared images of dusty Wolf-Rayet shells (Tuthill, Monnier, & Danchi 1999; Monnier, Tuthill, & Danchi 1999), the two order-of-magnitude slower winds around asymptotic giant branch (AGB) stars result in the requirement of longer time bases and extremely high-fidelity mapping schemes.

2. OBSERVATIONS AND RESULTS

2.1. Observations

Diffraction-limited images of IRC+10216 were obtained at seven separate epochs with the Keck I telescope, with dates and other observing details given in Tables 1 and 2. Observations used the technique of aperture-masking interferometry, by which starlight from the primary mirror is selectively blocked, with only a few regions of the pupil allowed to contribute to the final image. For observations...
of bright compact objects, of which IRC +10216 is a prime example, the methods of sparse pupil interferometry have been shown to be fully competitive with, or superior to, other techniques such as speckle interferometry. Statistical methods based on the maximum entropy technique (Sivia 1987) have been used to recover maps from the complex visibility data; however, alternate methods such as the CLEAN algorithm (Högman 1974) produced similar results. Data reduction and analysis procedures were also tested by observing a number of test objects, such as known binary stars, on each night. A detailed description of the Keck aperture-masking experiment covering the observational techniques, data reduction, and image reconstruction can be found in Tuthill et al. (2000).

At each epoch in Table 1, a number of observations of IRC +10216 were made, often with quite distinct experimental setups. Three different aperture masks were used over the course of the project, with the nonredundant Golay-type masks passing only a few percent and the partially redundant annulus mask passing around 10% of the unobstructed pupil. Three different filters were also employed at various epochs, with the bandpass characteristics given in Table 2. This diversity of observing parameters, while in part representing experimental evolution, allowed us to tailor the observations to conditions and specific requirements on a given night. However, no systematic differences were found when comparing maps from annulus and Golay data and, more significantly, from any of the different filters used (filters differ in bandwidth but have similar center frequencies; cf. Table 2). Thus, for the remainder of this work, all maps taken at one observing epoch are treated as measuring the same quantities.

### Table 1

| Epoch | Date      | Mask     | Filter | Phase |
|-------|-----------|----------|--------|-------|
| 1 …… | 1997 Jan 29 | Golay15  | kcont  | 0.72  |
| 2 …… | 1997 Dec 16 | Annulus  | kcont  | 0.72  |
| 3 …… | 1997 Dec 18 | Golay21  | kcont, ch4 | 1.23 |
| 4 …… | 1997 Apr 14 | Golay21  | ch4    | 1.41  |
| 5 …… | 1997 Apr 15 | Annulus  | ch4    | 1.41  |
| 6 …… | 1998 Jun 04 | Golay21  | ch4    | 1.49  |
| 7 …… | 1998 Jan 05 | Annulus  | ch4    | 1.83  |
| 8 …… | 1998 Jun 04 | Golay21  | ch4    | 1.83  |
| 9 …… | 1999 Feb 04 | Annulus  | ch4    | 1.88  |
| 10 …..| 1999 Apr 25 | Annulus  | k, ch4 | 2.00  |
| 11 ……| 1999 Apr 25 | Annulus  | ch4    | 2.00  |

a See Table 2 for filter wavelength information.
b Stellar phases from Monnier, Geballe, & Danchi 1998.

Two limitations of the interferometrically reconstructed maps should be mentioned. First, the absolute photometry, or surface brightness scale in the maps, is difficult to calibrate with any great accuracy. For this reason, images shown have fluxes scaled relative to the peak intensity in each map, and discussion will refer to these relative fluxes. Second, the closure phase method does not deliver absolute positional information, and the center of each map has been chosen to be the location of the brightest pixel.

### Table 2

| Name | Center (\(\lambda_o\)) (\(\mu m\)) | Bandwidth (\(\delta\lambda\)) (\(\mu m\)) |
|------|----------------------------------|----------------------------------|
| kcont | 2.260                            | 0.053                            |
| ch4   | 2.269                            | 0.155                            |
| k     | 2.214                            | 0.427                            |

2.2. Morphology of IRC +10216

Figure 1 shows maps of IRC +10216 from data spanning a period from 1997 January to 1999 April. In this figure, maps shown are the noise-weighted average over all image reconstructions from a given epoch (or, in the case of 1999 January/February, pair of epochs). Simple inspection shows that the basic morphology of the inner nebula surrounding IRC +10216 has been very well established in the K band. From the most prominent structures down to relatively minor features at only a few percent of the peak surface brightness, a high degree of consistency is found in the sequence of images. Furthermore, the early epoch images shown in Figure 1 are also in excellent agreement with recently published near-infrared images of Weigelt et al. (1998) and Haniff & Buscher (1998) (we refer collectively to these two papers as “WHB” hereafter).

In order to proceed with a quantitative analysis of the maps, a simple descriptive model has been used to identify and label features. WHB have labeled compact features A–D, with Weigelt et al. (1998) adding E and F which seem much less distinct. With the considerably higher resolution available from the Keck, these compact knots have in most cases been resolved into more complicated structures, and therefore a different approach is taken in describing the images, which we relate to the earlier schemes.

A skeleton diagram of our model, based on analysis of images from Figure 1, is given in Figure 2. The location of the brightest feature in all maps, the relatively compact core, appears as a plus symbol surrounded by rings showing its approximate extent (feature A of WHB). This core appears somewhat offset to the northwest from the center of an elongated, roughly elliptical region (features E and F of Weigelt et al. 1998). We refer to the core and these immediate surroundings as the southern component in Figure 2. The next most prominent structure in the maps is the linear extension to the north and northeast, which we have split into two: the shorter north arm (WHB feature C) and the more prominent, elongated northeast arm (WHB feature B). The important northeast arm we have modeled as a linear ridge of emission. Displaced to the east between these other features is a dimmer structure, consisting of multiple peaks we have labeled the eastern complex (WHB feature D). Although signal-to-noise ratio was not uniformly high enough to be assured of high-fidelity reconstructions of the eastern complex, for the purposes of characterizing the structure, we have labeled the most southerly portion cloud ECI (usually a little brighter and appearing like a ring or three peaks in a triangle), while in the more northern section we have been content to simply tag the location of the two most prominent peaks.

2.3. Proper Motions and Modeling

Having established in the previous section a framework for describing the appearance of the maps of IRC +10216,
Fig. 1.—Image reconstructions of IRC +10216 in the near-infrared $K$ band taken over a period from 1997 January to 1999 April. The nonlinear contour levels highlight the extended spatial structure. Each map presented is the average of between one and six individual maps, each taken at different times, and often with differing observing geometries, filters, and seeing conditions. By performing a noise-weighted average over a number of maps, random and systematic noise in the images could be suppressed for observations at a single epoch. The exception is the 1999 January/February map, where data were averaged over the two separate (but closely spaced) epochs. This was found to be necessary as poor data quality resulted in noisy maps over this period.
In addition to the motions of certain features, other changes are apparent with time in Figure 1, at a level of significance well above the level of noise in the maps. Two of these in particular are worth highlighting. The northeast arm, which in 1997 January ends in a bright, fairly compact knot, evolves through a stage where it is of fairly uniform brightness along its length (1998), and in the final measurements (1999) the extreme end of the arm has dimmed considerably. The second interesting change concerns the central core, which in 1997 January appears fairly circular and compact but by 1999 April clearly exhibits an extension to the southeast. Further discussion of these points is given in § 3 below.

2.4. Outflow Velocities

Having established the presence of motion between the components, it is possible to characterize the apparent outflow of material by watching the features which are presumably embedded within it. We restrict our attention to the northeast arm and EC1, as the more minor features are too near to the map noise level to make useful tag points for the flow. The first important question to be addressed is the assumption as to the origin of the flow. WHB present arguments that their component A, the compact core, be identified as the star itself. Certainly, features identified to be moving do appear to be moving away from a point to the south, and in our subsequent analysis we have assumed radial divergence from the compact core. However, there is no guarantee that any of the map features must be the stellar disk, which may lie behind some optically thick region, as is discussed further below.

It was fairly straightforward to project the motion of EC1 onto a vector beginning at the origin (the brightest pixel in the core; see Fig. 2). Displacement along this vector with time then gives a velocity. Motion of the northeast arm, however, is not so easy to quantify. The minimum possible apparent velocity consistent with the time sequence of images would have material in the arm moving to the northwest, perpendicular to its length. While giving a lower bound on the possible velocity, this motion is not consistent with spherical outflow from our defined origin and furthermore does not really describe the data as the arm would also need to grow in length. Instead, we have labeled points NE1 and NE2 near the beginning and end of the arm, respectively, and we measure the radial motion of these points from the origin. Since the arm has been fit as a linear ridge, two points are sufficient to completely determine its motion. Thus, our three trace points in the flow are EC1 and the two points NE1 and NE2 on the northeast arm, all of which are assumed to be radially diverging from the core.

Plotted in Figure 3 are the displacements from the origin through epochs t1–t4. Points labeled NE1 and NE2 identify fixed locations toward the ends of the northeast arm and are used further in the quantitative analysis described in the text.

we now proceed to examine the data for changes over the seven epochs. The easiest thing to look for is a change in the relative positions of the components. This was done with the use of a computer program which found the best-fit location of model components describing four features: the northeast arm, EC1, and two minor peaks in the eastern complex. As our maps have no associated astrometry, the registration between separate images is unknown and we have used the bright compact core as the fixed point against which to measure any motions. Note that fits were not made directly to the averaged images presented in Figure 1 but to the full seven epoch data set with multiple separate images at each epoch (comprising a total of 25 maps). This allowed errors to be determined on the locations of the features from the apparent spread of values over different maps.

All four features tracked were found to exhibit widening separations from the core as a function of time. This can be verified by visual inspection of the images of Figure 1 where the northward motion of the northeast arm is readily apparent without any assistance from computer model fits. Motions of the northeast arm and elements in the eastern complex including EC1 are shown in Figure 2. To avoid the confusion of seven sets of features on one plot, the motion is shown averaged into four time intervals (labeled t1–t4), as described in the caption.
too short to make this strategy worthwhile for data in
Figure 3. A uniform radial acceleration of 3.4 mas yr$^{-2}$ (see below) has been overplotted (dotted line) illustrating the dif-
ficulty of measuring such a small curvature of the velocity
day. However, some information on the flow dynamics can
be inferred from examination of the velocity field derived
from the maps. Specifically, the greater the distance from
the origin, the higher the outflow speed. Three possible
explanations for this finding are described below.

The acceleration of material over the region sampled by
the measurements may have been detected. This acceler-
cation can be easily visualized from the motion of the north-
east arm: the ridgelines of best fit are not parallel causing
the arm to tilt northward with time. In order to do this, the
far end of the arm (NE2) must be moving faster than the
near end (NE1). The three-flow velocity data points from
Figure 3 are consistent with a uniform radial acceleration of
3.4 $\pm$ 0.5 mas yr$^{-2}$ starting at a radius of 80 $\pm$ 20 mas.
As the principle acceleration mechanism is expected to be radiation
pressure from the central star, a uniform acceleration
law would not be expected. However, in a region as clearly
anisotropic as the inner dust shell of IRC +10216, flows
may be complex, and more realistic models will require
greater efforts both in modeling and in recovery of longer
time-baseline data.

A second possible explanation for the observed velocity
field arises from the ambiguities associated with the projec-
tion of three-dimensional structure onto the plane of the
sky. Such projected motions and velocities may give a mis-
leading view of the true flow structure. To take an extreme
example, the northeast arm may, in reality, be a fragment of
a circular arc, all of which is at a uniform distance from the
star and moving at a uniform velocity. However, when
viewed from a relatively acute projected angle, apparent
differences in separation and velocity will be recorded. For
a roughly spherical distribution of clumps at a uniform flow
speed, projection effects alone would result in slower appar-
ent speeds being observed closer to the star, mimicking an
acceleration. The uniform “acceleration” law given above
is appropriate for such a scenario, where the velocity will be
proportional to the displacement from the origin.

Finally, a third possibility which presents itself is that
faster material is found farther out (e.g., velocity law $V \propto R$), but without acceleration taking place over the
sampled region. The most obvious origin for such a flow
would be a stellar eruption ejecting material with a range of
velocities at some point in the past, allowing faster clumps
to move farther from the star. Under this scenario, back
projection of the flow through time, based on the NE1 and
NE2 velocities, implies that the northeast arm was created
in an event around JD 2,449,000 (about 1993 January) orig-
inating from a point some 90 mas from the core. Ideally,
the assumption of a single expulsion event could be tested with
three or more clumps by seeing if they appear to be diverg-
ing from a single point in space and time. Unfortunately, the
errors on the EC1 flow are too large to offer a meaningful
constraint, although a common origin for NE1, NE2, and
EC1 does fall within the errors.

In summary, although acceleration stands as a strong
candidate, the ambiguities of interpretation make it impos-
sible to claim a clear detection. Indeed, some combination
of all three effects discussed above may be needed to
account for the true angular velocity field. This highlights
the need for high-quality imaging over more extended
periods to follow clumps from birth to dispersal in the
extended shell. Despite the uncertainties, a plane-of-the-sky
assumption represents a simplest case and should give, at
the least, valid lower bounds to the velocity determinations
discussed here.

3. DISCUSSION

Taking the southern component and the northeast arm
as the dominant bright structures in our images, the bipo-
larity at position angle $\sim 20^\circ$ reported throughout the liter-
ature is confirmed here. However, at very high resolution,
complex and clumpy structures are revealed which do not
conform immediately to any simple axially symmetric
models. Perhaps one of the most striking features of the
maps of Figure 1 is the dark lane (see Fig. 2), around which
all the major structures are distributed. At all epochs, the
flux level in this hole, in close proximity to all the brightest
knots of emission, is consistent with a surface brightness of
$\leq 1\%$--2\% of the peak: similar to the noise level in the maps.
That such a dark region could exist in the heart of the
equatorial density enhancement, which we can see tilted toward us to the
south revealing the inner hot regions (southern component) and possibly the star (core). Clumpy features embedded in the outflow, such as the northeast arm and eastern complex, might have their origins in enhanced dust formation occurring above slowly evolving massive convective features (Weigelt et al. 1998) or magnetic spots (Soker & Clayton 1999) on the stellar surface. Interestingly, no changes observed over the seven epochs, which cover more than 1 pulsational cycle (~638 days), gave clear evidence for new dust nucleation (discounting the elongation of the core, discussed below). This is in accord with model dust shells (e.g., Winters et al. 1995) which show new layers of dust forming on timescales longer than 1 pulsation period.

Until further modeling can be completed, we confine further discussion here to the motion of material in the outflow. For features such as the northeast arm, it seems most likely that motions detected are simply the displacement of emitting material, and not some more exotic scenario such as the motion of a viewing hole in the dust, or a warm spot caused by a “searchlight beam” where the star shines through a moving window in the dust. The northeast arm does exhibit some common sense characteristics reinforcing this view, such as the flux from the bright knot at its extreme end, initially bright, fading as it moves outward and presumably farther from the central star (see § 2.3).

Perhaps the greatest uncertainties affecting the interpretation are the questions as to the origin and direction of the flow and the three-dimensional structure of the nebula. Although Figure 2 does appear to show that features are moving away from a point in the general location of the southern component, it was not possible to pin this down precisely. Worse, it was not possible to tell if the southern component and core were moving also: it may be the case that all features are diverging from the star which lies obscured behind the dark central band. A number of previous authors (WHB; Kastner & Weintraub 1994) have claimed that the central star is visible in near-infrared. The compact feature we have labeled the core has an approximate angular size of ~50 mas—close to the expected angular diameter of the stellar photosphere (Danchi et al. 1994; Monnier 1999). However, the progressive elongation of the core through time (see § 2.3; Fig. 1) is not easy to reconcile with this view. It is possible that the southeast extension we see is simply the newest condensation of dust moving from the star; however, for this to be the case the dust must be forming extremely close (≤2 R⊙) to the photosphere. The inner radius of the dust shell has been recently estimated at 4.5 R⊙ (Groenewegen 1997) and 6.8 R⊙ (Monnier 1999). It may also be possible that a binary companion is playing some role in this inner distortion, although it is highly unlikely that direct light from a main-sequence star could have been seen. In this work, the assumption has been made that the core does mark a fixed location associated with the star, with extra structure in the southern component arising from emission and/or partial obscuration from the inner boundary of the dust shell. Alternate scenarios, in which the core may also be moving, lead to modification of the derived velocities by up to a factor of 2.

The gas outflow velocity at large distances from the star is well established from CO line profile studies to be 14.5 km s^{-1}; however, as calculated by Groenewegen (1997), the dust will drift through the gas at 3 km s^{-1} resulting in a dust outflow speed of 17.5 km s^{-1}. Combining this with our maximum angular velocity of 25.5 mas yr^{-1} from Figure 3 yields a distance estimate of 145 pc to IRC+10216. This is in accord with modern estimates lying in the range 110–170 pc (Winters, Dominik, & Sedlmayr 1994; Le Bertre 1997; Groenewegen, Van Der Veen, & Matthews 1998). However, there are too many uncertainties involved to place high confidence in this result. In addition to the geometric ambiguities already mentioned, it is unclear if the dust clump followed here (NE2) has finished accelerating and is at its terminal velocity. Furthermore, the value of V∞ measured in the spherical molecular shell may not be a good measure of the inner dust motions. It is difficult to imagine that any dramatic change from spherical outflow to an equatorial disk and bipolar lobes in IRC+10216 did not also entail changes in the velocity structure.

Taking a distance of 145 pc, proper motions of 11.5, 17.8, and 25.5 mas yr^{-1} (Fig. 3) imply outflow velocities of 7.9, 12.2, and 17.5 km s^{-1} for points NE1, EC1, and NE2, respectively. As computed above, the velocity structure is consistent with an apparent uniform acceleration of 3.4 ± 0.5 mas yr^{-2} from rest at 80 ± 20 mas. However, the projection of a three-dimensional motion onto the plane of the sky and unknowns associated with the initial conditions of each clump may also account for the range of observed flow speeds. Models of radiatively driven dust acceleration predict a more complicated velocity law dependent upon many properties of the star and the outflowing gas and dust (Kwok 1975; Papoular & Pégourié 1986). Detailed comparison with such predictions is premature until the velocity of a single feature can be shown to be changing over time.

4. CONCLUSIONS

Diffraction-limited images recovered using interferometric techniques from a multipieoch study spanning more than 2 yr at the Keck 1 telescope are presented. Taken in the near-infrared K band, the maps have revealed an asymmetric and clumpy structure at angular resolutions exceeding the expected diameter of the stellar photosphere (~50 mas). The most likely morphology for the circumstellar environment is an optically thick circumstellar disc or torus, possibly tilted toward the line of sight in the south revealing the hot inner cavity and emission from the stellar photosphere. The angular separations of clumps of material thought to be in the northern bipolar lobe have been followed over time, revealing increasing separation from the compact core to the south. Outflow velocities derived from this motion are consistent with estimates of the radial outflow velocity (from CO measurements) and the expected distance. Clumps at greater distances from the core were found to show increasing velocities, which may be taken as evidence for acceleration in the inner regions, the effects of geometrical projection, or the result of a past event which ejected material with a range of velocities. In addition to the changing separations of components, the appearance of the inner nebula was found to be evolving in other ways; however, none were interpreted as evidence for new dust condensation over the pulsation cycle. Further modeling of this system is currently under way and will be presented in a subsequent paper.

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