SPECTROSCOPIC STUDIES OF IRC+10216 AND SIMILAR OBJECTS

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ABSTRACT

Spectroscopy of circumstellar molecular species in the 2-14μm range provides evidence for a range of shell optical depths in the +10216 class of stars. In some cases a photospheric spectrum is present. The spectrum of +10216 shows absorption over a range of velocities including two distinct velocities of different excitation temperature. The occurrence of multiple velocities may be common in similar objects.

1. OBSERVATIONS

IRC+10216 is the archetype of a class of cool carbon stars. These very cool, probably Mira type, stars are ejecting substantial quantities of dust and gas. With the techniques of infrared and millimeter spectroscopy and infrared interferometry it is possible to examine the dynamics of the ejection process. These observations will lay the foundations for an interpretation of the ejection mechanisms and the chemical kinetics of the circumstellar and nascent interstellar material.

We have recorded high resolution (2-3 km/sec) infrared spectra of four members of the +10216 class. The objects observed (+10216, +30219, -10236 and +50096) exhibit a range of [2μm-3μm] color temperatures (550, 680, 830 and 975K respectively). As shown below, these objects substantiate the expected correlation between color temperature and optical depth in the circumstellar shell. The spectral range covered includes all terrestrial windows from 2 to 13.5μm. Circumstellar molecular absorption due to CO, HCN, C_2H_2 and CH_4 has been detected in fundamental, overtone and combination bands (e.g. Ridgway et al. 1976, Ridgway et al. 1978, Hall and Ridgway 1978). For the study of temperature-density distributions and dynamics the CO bands are uniquely valuable. Each band provides many spectral lines of various lower state excitations and line strengths.

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Dynamical information is obtainable from even moderate resolution spectra. In Figure 1 we show the LSR velocity of line center for each detected line in just the 2-0 band of CO. (The noise can be estimated from the scatter between adjacent points.) In each figure the blue edge of CO microwave thermal emission has been noted (tip of arrow), and also the microwave line-center if on-scale (origin of arrow). Note the smooth variation of velocity with excitation (rotational quantum of the lower state). The observed absorption velocities lie in the range expected for an expanding shell. In the case of +50096, the least obscured of the four objects, the absorption line velocities do not vary strongly with excitation, but two components appear: one near the velo-

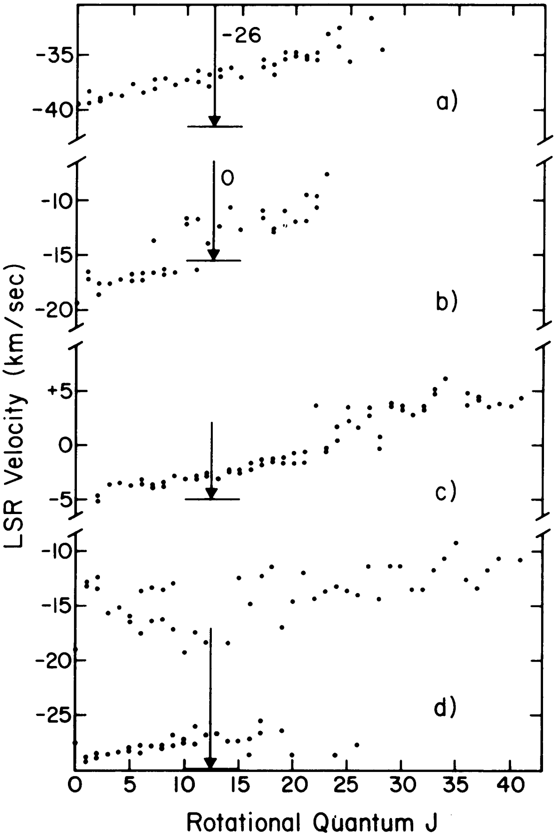

Fig. 1. CO v = 2-0 line positions. a) IRC+10216. b) IRC+30219. c) IRC-10236. d) IRC+50096. Note two velocity components in part d. The arrow indicates the velocity of J = 1-0 emission (Wilson et al. 1973, Kuiper et al. 1976, Zuckerman et al. 1977, Zuckerman et al. 1978). The origin of the arrow indicates 1-0 line center velocity (or labeled if off-scale), and the tip is at the blue edge. Observation dates are 15 Oct 1978, 17 Oct. 1978, 19 Feb. 1979, and 17 Oct. 1978. To convert to heliocentric velocity add 6.8, 1.5, 9.8, and 1.6 km/sec.

city of microwave line-center (presumed center of mass velocity) and one at the blue edge (relative expansion velocity).

For a more detailed understanding of the velocities, it is necessary to study the line profiles at higher resolution. In Figure 2 several CO line profiles of +10216 have been collected. At the top is the CO microwave profile measured by Kuiper et al. (1976). For each of the infrared profiles, several CO lines of similar excitation have been

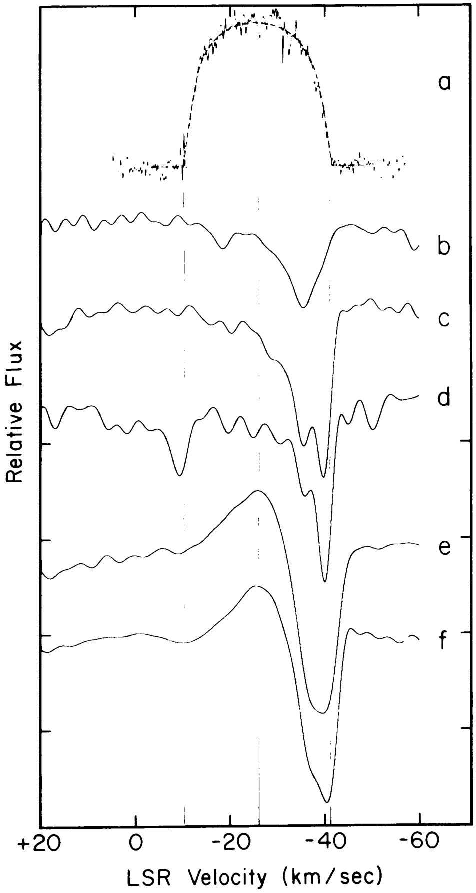

Fig. 2. CO line profiles in +10216. a) J = 1-0 emission from Kuiper et al. (1976). b) v = 2-0 absorption, high excitation profile. c) 2-0 medium excitation profile. d) 2-0 low excitation profile. e) v = 1-0 absorption low excitation profile (from ^{13}CO). f) 1-0 high excitation profile. Zero flux levels for spectra b-e are indicated by tic marks. The fundamental band observation date was 13 Oct. 1978 and overtone observations were 15 Oct. 1978. This was shortly after expected maximum in the light curve of +10216. Terrestrial absorption lines appear in the wings of several of the profiles.

averaged to reduce noise. First consider the medium excitation lines in the overtone band (Fig. 2c). Line doubling is evident; the splitting would be more complete in a fully resolved spectrum. The blue component appears in the low excitation overtone line (2d) but not in the high excitation line (2b). From the distribution of strength with excitation we conclude that the temperature of the gas producing the blue absorption is ∿ 150-250K. From similar considerations, the red component must arise in gas ∿ 300-700K. (In addition to observational error, it is probable that a range of gas temperatures contribute to each component.) The red (hot) absorption also has a broad red wing which probably extends to the red side of the center-of-mass velocity.

The fundamental band low and high excitation profiles (Figures 2 e and f) show the doubling as an asymmetry. In addition, a strong P Cygni type emission appears in the fundamental. Such an emission is not expected in the overtone, since the fundamental is the preferred route for emission from excited CO.

2. DISCUSSION

A simple interpretation of the +10216 line shape requires two regimes of absorption with distinct temperatures and velocities. In a spherically symmetric geometry, we might imagine a warm inner shell expanding at 11 km/sec and a cool outer shell expanding at 16 km/sec. The redward extension of the overtone absorption to the center-of-mass velocity can be explained by simple geometry. The line of sight to the edge of the continuum source intercepts radially flowing gas with projected velocity less than the expansion velocity by an amount dependent on the radial distance of the gas from the continuum source. For gas near the continuum source (the hot component) this produces an absorption wing extending as far to the red as the center of mass velocity. For gas distant from the continuum source (the cool component) the velocity spread due to this projection effect is small. These considerations will not account for absorption to the red side of the center-of-mass velocity. It may be possible to account for the extended profile if we hypothesize that a portion of the 2.4μm flux is scattered at least once so that we see light emitted from the back hemisphere of the continuum source. The P Cygni emission is probably associated with the hot absorption component, and it appears that the emission approximately equals the corresponding absorption. This indicates that the scattering region is mostly within our 2.5 arc-sec aperture, and also that the 0.4 arc-sec continuum source does not substantially occult the scattering region. The angular diameter of the cool outer shell probably exceeds the instrument field-of-view; hence, no significant re-emission is expected in the line wing.

It may be difficult to account for a higher expansion velocity in the outer layers with a steady-state model. If the acceleration is to be attributed to radiation pressure, it would be necessary for a radiation pressure gradient within the observed column to be contrived so as to give a discrete boost to the gas velocity. Of course, one might appeal to catastrophism (shell ejection, etc.). But from the similarities between Figures 1a, b, and c, it appears that the combination of gas temperatures and velocities found in +10216 recur in similar objects, weighing against interpretations invoking discrete events. If we abandon spherical symmetry (as we must according to McCarthy et al. 1978) then we may readily sketch diagrams with various segments of disks and shells in the line of sight, each with distinct temperature and velocity. A suitable evaluation of such possibilities requires a comprehensive synthesis of spectral and spatial data.

In +10216 the absence of CO bandheads indicates that less than 6 percent of the flux at 2.3μm is photospheric radiation (direct or scattered). From the known flux, and an assumed stellar temperature > 1000K, it follows that the star is obliterated by a continuum absorption optical depth greater than 5.5. In -10236 and +50096, however, we see evidence for a photospheric spectrum. In both cases the 2μm CO bands extend to line excitation of J∿40 with well-developed band heads. The red components of the lines have velocities near the center-of-mass velocity. In Figure 3, the low excitation line profile in the CO 2-0 band of +50096 substantiates a photospheric origin for this absorption. The hot absorption profile has the broad, flat-bottomed shape of a photospheric line, though diluted by circumstellar continuum emission. A single expanding cool shell produces a blue-shifted line. The photospheric component has an excitation temperature ∿1300K, and the circumstellar component ∿500K. In -10236 the photospheric spectrum is not resolved from the circumstellar. The resemblance to +50096 suggests a similar situation but with greater circumstellar obscuration and a lower shell expansion velocity (6 vs 13 km/sec). In +50096 and -10236 we estimate absorption optical depths ∿ 0.7 and 1.4 respectively.

On the basis of this preliminary study, the +10216 type objects appear to have a range of shell optical depths. The more heavily obscured examples show a double shell velocity structure. Yet cooler, possibly more heavily obscured +10216 objects are known, as well as a

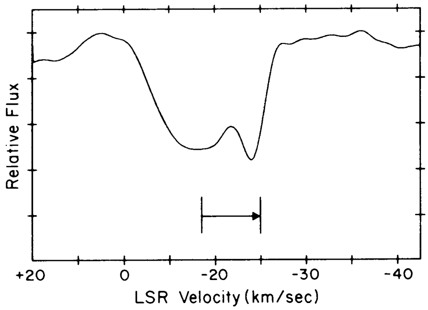

Fig. 3. CO v = 2-0 low excitation line profile in IRC+50096. The origin and tip of arrow indicate center and blue edge of J = 1-0 emission (Zuckerman et al 1977).

range of less obscured stars that span the gap from, for example, the Mira V Cygni to IRC+50096. We plan to extend our survey to these members of the +10216 class. Since each closer look at +10216 reveals yet more complexity, this source also deserves more detailed scrutiny.

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