The IRC +10216 Circumstellar Shell [and Discussion]

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The IRC +10216 circumstellar shell

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Spectroscopic studies of IRC +10 216 reveal numerous molecular species and at least two grain species. To define the composition of the ejected material and confirm the activity of chemical processes in the expanding shell, it is necessary to integrate infrared and microwave spectroscopic results with multi-spectral spatial mapping.

Introduction

The invention of microwave spectroscopy and the subsequent development of microwave astronomy has revealed two great régimes of interstellar chemistry: the dense molecular clouds and the circumstellar shells. The shell stars fall into two types differentiated by elemental abundances, with the pattern of molecular composition sharply different for the carbon-rich and for the oxygen-rich (Zuckerman 1980). The prototypical carbon-rich shell star is IRC +10216, so heavily enshrouded in dust that, although it is one of the 'brightest' stars in the sky the apparent magnitude at visible wavelengths is *ca.* 18. Extensive observational work, much of it innovative, permits a detailed description of this interesting star.

IRC +10216

Owing to the large extinction of the IRC +10 216 shell, visible radiation from the stellar surface is detectable only with difficulty, and even then the photons have probably undergone numerous scatterings in the dense, inner regions of the shell. However, the near infrared spectrum determines a general spectral class (C type). Further, the flux variations at all wavelengths indicate a long-period variable of the Mira type. An estimate of the stellar luminosity (*ca.* $5 \times 10^4\ L_\odot$) is consistent with the idea that IRC +10216 is among the brightest of the C type stars, and this is intuitively reasonable since the extreme mass loss rate producing the thick shell would plausibly be related to high luminosity.

As with the oxygen-rich shells, the presence of dust grain material is deduced from optical–infrared extinction and i.r. thermal emission. A spectral signature near 11 μm indicates the possible presence of SiC grains, but emission at long wavelengths requires another material. Graphite, long considered a candidate, has recently fallen from favour for reasons mentioned below, but some form of carbon solids must be present.

The gaseous material in the shell has been extensively studied by microwave and infrared spectroscopy, and is directly detectable out to great distances (more than 1000 stellar radii). The remarkable diversity of molecular species identified has stimulated substantial interest. Particularly, the long carbon chains (HC_5N and HC_7N), indicate a surprisingly high abundance of relatively complex constituents.

Why is IRC +10216 important?

As a prototypical source of interstellar dust, IRC +10 216 deserves careful scrutiny; estimates of the dust characteristics and ejection rates are therefore of great interest. Furthermore, IRC +10216 is evolving rapidly. It is an extreme example of the mass loss process. The trigger and mechanism of mass loss from cool stars is not at all understood, and an extreme case may provide clues, or at least limits, to the possible physical mechanisms.

In the study of stellar evolution, mass loss is one of the clearly deficient features of theoretical computations. Certainly in some evolutionary phases, mass loss produces spectacular changes in stellar structure. The transition from a cool, luminous red giant to a planetary nebula is probably due to mass ejection – very possibly continuous, non-explosive ejection – and in IRC +10216 we may witness the process in its most active phase (Kwok 1980).

Quite aside from the implications for stellar evolution and the interstellar environment, the IRC +10216 shell deserves careful study on its own merits. The continuous outflow of gaseous material from the stellar surface provides a natural laboratory with a running experiment in the chemical kinetics of cooling, expanding gas. From below the surface where molecular formation is negligible, through the photosphere where near-equilibrium conditions may apply, into the expanding, cooling circumstellar regions, with dust grain formation, through an extensive cool region, into the outermost limits of the shell where the ambient u.v. photon flux plays a role, the ejected material samples large variations of temperature and density. At present virtually nothing is known of the chemical processes active in the shell, but a substantial amount is now known about the chemical products, with at least 17 species identified, as well as many isotopic variants (McCabe *et al.* 1979). But forming a reasonably complete picture of the shell requires an appeal to a much wider variety of data.

The available data

First, of course, is the broad-band flux distribution, which first signalled the unusual nature of IRC +10216. The distribution is unusually well studied in the i.r. out to 1000 μm. The flux peak is near 5 μm, indicating an equivalent black-body temperature of *ca.* 650 K. Both the flux and the shape of the distribution vary cyclically, and the period (*ca.* 600 days) and amplitude (*ca.* 2 magnitudes at 2 μm) are an unambiguous signature for an underlying Mira type variable. From the flux distribution, several characteristics of the shell may be deduced. The faint visual flux determines the extinction at that wavelength (e.g. $\tau \approx 12$ at 0.7 μm). The wavelength of the flux peak gives a crude characteristic temperature, and hence an approximate radius, for the emitting region. This may be interpreted as the 'outer' radius of the dense inner part of the shell. For a stellar temperature of *ca.* 2000–2500 K, this implies a dimension *ca.* 10–15 times the stellar radius. The far infrared flux distribution is dominated by emission from the cool, outer regions of the shell, but does not yield a ready intuitive interpretation.

Almost without exception, the flux measurements represent an integral over three spatial dimensions of the interesting physical variables; dust densities, grain size distributions, opacities and temperature distribution. The data obviously cannot be inverted to determine these quantities, although many studies of the photometric characteristics indicate consistency with specific possibilities.

A few measurements of the radiometric characteristics of IRC +10216 provide more detailed information. Interferometric measurements of spatial intensity distribution have been applied to IRC +10216. The interferometric results reported to a date are one-dimensional measurements, and hence they study a strip-brightness distribution, which is still a two-dimensional integral over the radiative properties of the dust. Actually, the success is only partial, since the interferometric measurements at present yield a measure of the spatial power spectrum which well determines the characteristic angular extent of the emitting region, but leaves the details only poorly or not at all elucidated.

Improvements in i.r. interferometry – which will certainly be assured by further developments in detector technology and observational technique – should eventually provide detailed, multi-wavelength, two-dimensional intensity maps of the continuum intensity distribution. Already, however, interferometric measures, repeated at multiple position angles, have shown an asymmetry in the i.r. emission, consistent with a 2:1 or 3:1 ratio in the axes of an elliptical approximation to the distribution of intensity (McCarthy *et al.* 1980). This asymmetry is a very important result. Where may its origin be found? With such a high mass ejection rate, it must reflect a stellar characteristic. The rotation or magnetic field axes are obvious possibilities. But in such a large star (*ca.* 10 AU) both angular velocity and magnetic forces must be small (compared with, e.g., convective or shock wave velocities and radiation pressure on dust).

Spectroscopic measurements provide very different types of information, with each technique and spectral region leading to unique results. The microwave measurements again represent a three-dimensional integral, here over gas density and excitation conditions (Kwan & Hill 1977). But for molecular emission, the parameters of the emission process (excitation cross sections, emission probabilities) are generally known or measurable. The detection of characteristic microwave transitions uniquely specifies a gas constituent and also provides some kinematic information. The integration over the entire shell gives the microwave technique a sensitivity to rather small concentrations of a particular molecular species (as low as 0.01 molecule/cm^3). But the price is a loss of detailed information, so, for example, in spite of excellent velocity resolution, the technique will not directly discriminate between gas ejection and gas infall. In the future, the development of microwave interferometry will provide unique information, especially about velocity fields in the outer regions of the shell.

I.r. spectroscopy records shell molecular transitions as seen in absorption against the continuum from the hot, inner dust shell. The gas studied is the column in line of sight to the continuum source. Since this source is relatively small (*ca.* 0.4″) the degradation of information is only a one-dimensional integral over the spatial distribution of material. Actually, the situation is even more favourable. Empirically, it is found that – at least along our line of sight – material is spread over a range of velocities consistent with continuous outward acceleration throughout the shell (Ridgway & Hall 1979). Since the different velocities map into a range of spectral frequencies, even the ‘degeneracy’ of information due to the one-dimensional integration is partly broken.

Another valuable characteristic of the i.r. is the multiplicity of molecular transitions available. Each species generally displays entire bands of transitions with varying strength and temperature dependence. In spite of this abundant information, it is still not possible to invert the data uniquely to determine the physical parameters of the shell. However, it is possible to identify several velocity régimes, and to specify the associated excitation temperature parameters, which describe in some detail characteristics of the shell in specific restricted spatial locations.

This brief, qualitative summary of the observational results does nothing to indicate the very large volume of published material, with many pages frequently devoted to a single molecule, a single spectral line, a single photometric datum. And yet no comprehensive review of this material has yet appeared. The reason is not hard to find. The diversity of observational techniques has produced a diversity of information. It is exceedingly difficult to incorporate this material into a comprehensive picture.

DIFFICULTIES

Numerous difficulties are encountered in the attempt to arrive at a detailed understanding of the IRC +10216 shell. A major problem in the analysis of observations arises in the fact, noted earlier, that most types of measurement reveal only integrated characteristics, averaged over physically distinct regions, often over large variations in physical parameters. The low information content of the resulting data impedes unique assignment of, for example, dust temperature, since a particular flux level may be due to an uncertain mix of small quantities of high-temperature material and larger quantities of low-temperature material, distributed over many astronomical units of the shell (Schmid-Burgk & Scholz 1976).

Another problem is in drawing a physical connection between observational data that are related qualitatively but not directly. For example, CO emission detected in millimetre measurements and CO absorption detected in i.r. spectra are clearly related, but in fact arise in distinct regions of the shell. The microwave spectrum is dominated by the outer envelope, while the i.r. absorption spectrum gives strong weight to the inner regions.

At the theoretical level, the relevant physics is not fully understood. The underlying mechanism of mass loss from cool stars is not known. Nucleation of dust grains and destruction by radiative and kinetic processes are provisionally described (Draine 1981), but verification of theory is minimal and actual parameters are generally not available. Chemistry on surfaces may be important, but the subject is largely speculative. Of course, progress in the theoretical areas may be expected, but it will probably be guided, or at least stimulated, by progress in discriminating observational capabilities.

In a more practical vein, many physical characteristics of the constituent gas in the shell are not known. Rates for most of the molecular reactions have not been measured. Collisional excitation rates for even many common molecular species are not available. The dust characteristics are a more difficult problem, since composition, atomic structure, size and shape are all to be determined (it is to be hoped) by observation.

A necessary approach to integrating the data, resolving the uncertainties in theory and evaluating the unavailable physical constants is the detailed modelling of the radiative, dynamical and chemical characteristics of the shell.

STATUS OF THE ENVELOPE MODELS

Simultaneous with the advent of high-resolution infrared spectroscopy and interferometry has been the development of powerful numerical techniques that permit an accurate treatment of the effects of geometric extension and velocity fields on continuum and spectral line formation.

Using these numerical and experimental techniques, we are attempting a semi-empirical diagnostic approach to map the gas and dust distributions in IRC +10216.

In analysing the continuum energy distribution, the equations of transfer and radiative equilibrium are simultaneously solved, in spherical geometry, to determine self-consistently the radiation field and the dust temperature distribution.

The most comprehensive published analysis of the IRC +10216 dust envelope involves a graphite SiC mixture extending from 20 R_* to 5000 R_* (Mitchell & Robinson 1980). This model (calculated by using the above numerical method), with an $r^{-1.3}$ dust density distribution, provides excellent agreement with the observed 1–1000 μm flux. However, the flux distribution alone does not adequately constrain the dust temperature distribution.

A recent lunar occultation observed at 5 μm confirms earlier interferometric results at 2 μm, requiring considerable dust within a projected radial distance of 2 R_* along the minor axis of the envelope. We have modelled this occultation with a two-component dust mixture of SiC and amorphous carbon, with $N_{\text{dust}} \approx r^{-1.3}$ in the range 2–8 R_*. The presence of dust emission near 2 R_* requires a dielectric dust material in that region of the shell, since the inverse greenhouse effect provides a dust temperature that reproduces the central brightness distribution without requiring grain temperature above the vaporization temperature. SiC is indicated for this constituent by the 11 μm spectral feature. Amorphous carbon has a much weaker wavelength dependence of the far i.r. opacity ($Q_{\text{ext}} \approx 1/\lambda$) (Koicke *et al.* 1980) than graphite ($1/\lambda^2$) and is strongly preferred to match the far i.r. flux distribution. The model is also consistent with interferometry at 2 and 11 μm (McCarthy *et al.* 1979; Sutton *et al.* 1979).

Infrared spectral observations of the CO first overtone near 2.3 μm show absorption over a considerable range of velocities: from −14 km/s to +20 km/s (relative to the presumed stellar velocity), with strong, distinct absorptions at −2.5, −10.0 and −13.5 km/s, having rotational temperatures of *ca.* 950 K, 500 K and 150 K respectively.

The 2 μm dust optical depth, $\tau \approx 6$, indicates that the redward absorption is probably not directly received photospheric radiation. Recent Monte Carlo calculations (C. J. Romanik & C. M. Leung, personal communication 1981) on the effects of an expanding dust envelope on an underlying photospheric absorption line indicate that the redward absorption could be produced by high albedo dust (SiC) scattering of photospheric radiation.

In analysing the CO fundamental and first overtone observations, a co-moving-frame solution of the transfer equation in an expanding spherical geometry is effected. The model for the intermixed dust is that which best matches the observed dust envelope spatial and spectral characteristic noted above.

An obvious interpretation of the component structure in the observations at 2 μm involves discrete shells from episodic mass loss (Ridgway 1981). However, such a component structure can be produced in flows with a continuous matter distribution. All that is required are regions where the flow velocity changes rather slowly with distance. Such a distribution might naturally ensue if several condensation events occurred in the circumstellar envelope, producing radial régimes of rapid acceleration separated by regions of approximately constant velocity. In this regard, it may be significant that in modelling the grain distribution we were forced to adopt a two-component distribution with different radii for the onset of condensation.

Our initial two-level atom calculations show that a continuous-flow scenario can produce good agreement with both the continuum intensity distribution and the spectral observations.

Owing to the low densities and the intense 5 μm radiation field, a considerable CO vibrational disequilibrium exists. A method of solving the coupled co-moving-frame radiative transfer and statistical equilibrium equations is now being implemented to represent more accurately the CO vibrational excitation.

Much remains to be done in the modelling. Generalization of the radiative equilibrium constraint to include mechanical equilibrium by including dust condensation, gas heating by gas–grain collisions, gas cooling by adiabatic expansion and millimetre emission (Kwan & Hill 1977) are required to calculate fully consistent dust and gas densities, temperatures and velocity fields. Equally important, the global deviations from spherical symmetry must be addressed. These elaborations of the shell modelling procedure will provide a secure basis for the interpretation of spectral evidence for envelope chemistry.

Concurrent progress in studies of Mira stars, especially including kinematics of the pulsating atmosphere, shock-wave phenomena and gas flow in the near circumstellar region (Hinkle *et al.* 1981) further defines boundary conditions on the mass loss process in IRC +10216 These and other developments suggest that comprehensive modelling of the envelope may be possible in the near future.

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Discussion

E. M. McCABE (*C.E.G.B., Marchwood Engineering Laboratories, Southampton, U.K.*). Eighteen molecules have now been identified in the shell of IRC +10216. Molecular equilibrium abundances can be calculated for 14 of these for a range of pressures and temperatures. I used such calculations to predict the observed abundance of ethylene, C_2H_4, since it is possible to choose conditions that fit all but four observed molecular abundances. In particular the low observed abundance of SiO and SiS relative to equilibrium calculations are further evidence for the inverse greenhouse effect mentioned by Dr Ridgway. The effect causes SiC grains to condense at high gas temperatures.