The southern active region Sgr B2 (M) exhibits pronounced emission from SO_2. About 20% of the lines have not been identified and the identifications of at least another 10% are very questionable. It has to be stressed that the work to identify the lines is far from completed yet. One of the lines preliminarily identified is another HDO line, which supports the identification at 80 GHz. Still the line density is high enough to make a two-transition identification doubtful. We hope to be able to confirm the HDO identification in our next observing run (June 1989).

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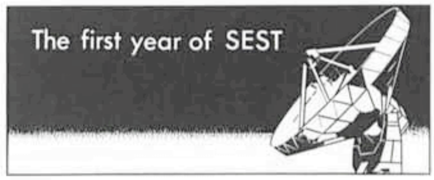
Evolved Stars

L.-Å. Nyman, SEST, La Silla



Introduction

Studies of evolved stars using sub-mm and mm-wave telescopes such as the SEST are mainly concerned with the very last stages of the life of a star, when it throws away its outer envelope and is surrounded by a shell of dust and gas. The dust obscures the star optically and most studies of stars at this stage of their evolution have been made in the radio and infrared regions of the spectrum. The circumstellar gas consists mainly of molecular hydrogen, H_2, but also of other less abundant molecules (e.g. CO, SiO, OH, H_2O, HCN, etc.), which are important since they radiate in the radio region, something that is not these case for molecular hydrogen. These molecules can be used to study the properties of the circumstellar envelope (CSE), e.g. to determine mass-loss rates, which are important for the evolution of the star, and to study the chemistry of the envelope.

These studies are important because the envelope contains processed material from the interior of the star that is now returned to the interstellar medium. The material will eventually be incorporated into new stars, making our Galaxy evolve chemically. The mass loss is important for the evolution of a star, since its end point is determined by how massive it is. A star with a mass $> 1.4\ M_\odot$ should end as a supernova, but because of the extensive mass loss in the final stages of its life, even a star of $10\ M_\odot$ will lose enough mass to put it below this limit, and it will end as a planetary nebula and later as a white dwarf. Many of the observations with the SEST telescope have been made of stars at different stages in the final point of their lives and a brief summary of stellar evolution will be given below.

Stellar Evolution

Stars with masses $< 10\ M_\odot$ spend most of their lives on the main sequence, quietly burning hydrogen to helium in the core. When the hydrogen is exhausted in the core, the star moves up the Red Giant Branch (RGB) burning helium in a shell around the core, which is contracting and becoming hotter and hotter. Finally it is hot enough for helium to start burning, and the star moves to the horizontal branch burning helium to carbon and oxygen. Eventually the helium is exhausted in the core and the star starts to move up the Asymptotic Giant Branch (AGB). At this stage it consists of a degenerate carbon-oxygen core surrounded by a thin helium burning shell.

It will now reach a phase in its life where many things will happen on a relatively short time scale. When all the helium in the core has been converted to carbon and oxygen, hydrogen and helium will start to burn alternately in a thin shell around the core. Every time a critical mass of helium has been processed from the hydrogen burning it ignites with a flash, a thermal pulse (TP). Between the helium flashes a deep convection layer brings up processed material to the surface of the star and it may even change its composition from being oxygen-rich to carbon-rich. The star will also become unstable and start to oscillate. The pulsations will form shock waves in the photosphere, supplying energy to lift the gas to regions that are cool enough for dust formation. The radiation pressure on the dust will accelerate it away from the star dragging the gas along with it, forming an expanding CSE.

In the final stages of the AGB the mass loss increases rapidly and a superwind occurs. Almost all the matter in the hydrogen envelope is stripped from the star. The remnant core contracts rapidly at constant luminosity and the ejected material drifts outward. When the surface temperature is hot enough to produce UV photons, the ejected gas is ionized and a planetary nebula (PN) is formed. Eventually the gas disperses and the star will become a white dwarf.

Since the star is surrounded by a thick dust shell during the last phases of its life, it is difficult to study it optically. The

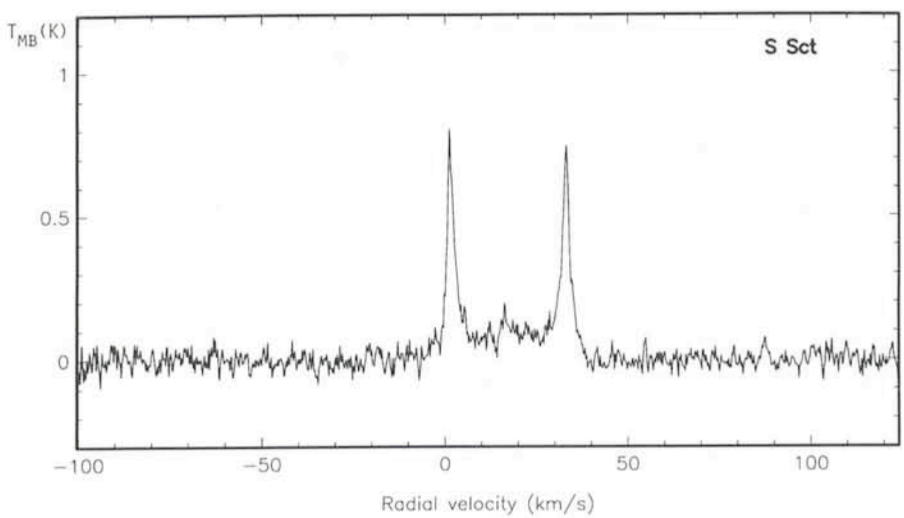


Figure 1: *A ^{12}CO (J = 1-0) spectrum of the bright carbon star S Sct. The double-peaked line profile and the map data suggest that the circumstellar envelope is detached from the star, i.e., its mass loss has decreased considerably during the last few thousand years. This may be an effect of a thermal pulse during the AGB evolution.*

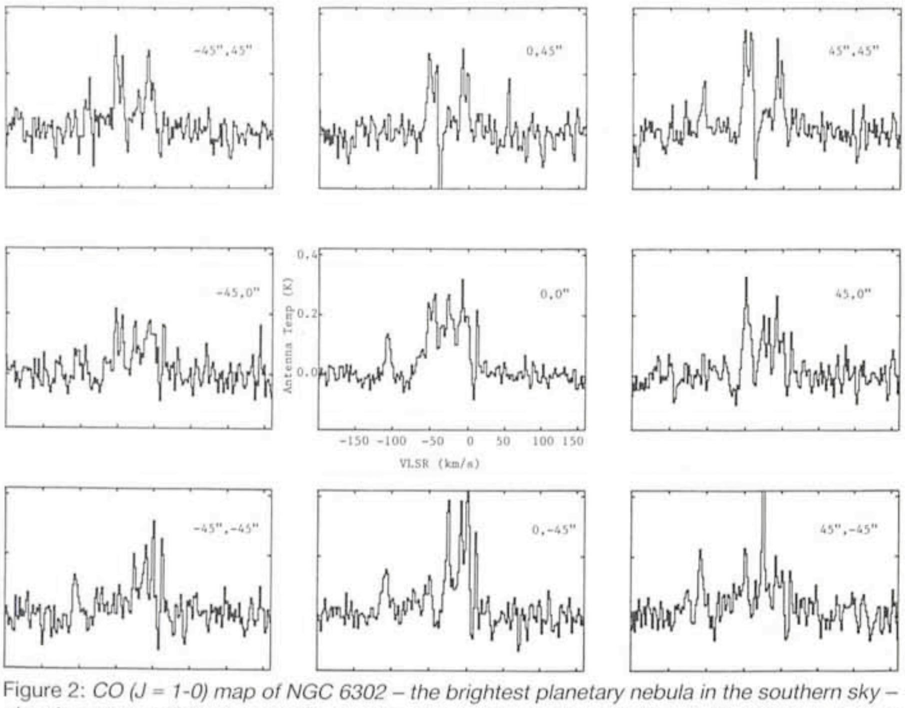


Figure 2: *CO (J = 1-0) map of NGC 6302 – the brightest planetary nebula in the southern sky – showing several distinct, spatially-variable, kinematic components (Sahai, R., Wooten, A., and Clegg, R. E. S.).*

dust radiates in the infrared, however, mainly between 2 and 100 μm, and infrared observations (especially those of the IRAS satellite) have given us insight into the properties of CSEs and stellar evolution. Van der Veen and Habing (1988) have studied the IRAS two-colour diagram (F_{60}/F_{25} versus F_{25}/F_{12}) in the region where CSEs are situated and interpreted the distribution of IRAS point sources together with other properties such as variability, etc., as an evolutionary sequence of increasing mass-loss rate, i.e. the IRAS two-colour diagram can be used to study the evolution of a star on the AGB and beyond.

In their scenario a star becomes variable somewhere on the AGB, maybe during the thermal pulses, and starts to lose mass. The mass-loss rate is fairly low in the beginning, $\sim 10^{-7}\ M_\odot\ yr^{-1}$. This is the region where Mira variables are situated. The mass-loss rate then gradually increases to a few times $10^{-5}\ M_\odot\ yr^{-1}$ and the star will be surrounded by a thick CSE, moving along the evolutionary track in the two-colour diagram. The star is now obscured and in this region we find the OH/IR objects. The mass-loss rate may not be continuous; during a thermal pulse the stellar oscillations may stop for some time, inhibiting the mass loss, and then start again. After some time the variability decreases, the mass loss stops and the star will become a planetary nebula. The planetary nebulae and their progenitors, the protoplanetary nebulae (PPN), are situated in certain parts of the two-colour diagram, thus making it possible to find candidates for further observations at this interesting stage in the life of a star.

Sometime during the evolution of some stars, enough processed material from the interior may have been brought up to the surface to change the composition of the star from oxygen-to carbon-rich. A few carbon stars with oxygen-rich CSEs have been observed, supporting this idea.

Circumstellar Molecules

The gas in the CSEs has mainly been studied through observations of molecular transitions in the radio region (some molecules have also been detected in their infrared transitions). So far, 36 molecules have been detected in CSEs (Olofsson, 1989). The strongest emission lines are produced by the SiO, H_2O, and OH molecules, situated in oxygen-rich envelopes. The population in some of their transitions may under certain conditions become inverted and the molecules will act as amplifiers, i.e. they will amplify the background emission at the frequency of the transition; they are so called *masers*.

The SiO masers are situated close to the surface of the star while the H_2O and OH masers are located further out, thus these molecules probe different parts of the envelope. Especially the OH masers have been useful to determine mass-loss rates and also the distances to stars.

Another useful molecule for studies of CSEs is CO. It is found both in oxygen- and carbon-rich envelopes, it is the most abundant molecule next to H_2, and can be used to determine mass-loss rates and other properties of the envelope. A large fraction of the observing time on the SEST telescope has been spent on observations of CO in different samples of stars at various stages in their evolution. Compared to the oxygen-rich envelopes the carbon-rich envelopes contain a variety of molecules, among them carbon chain molecules (HC_3N, HC_7N, C_4H, etc.) and ring-like molecules (C_3H_2, SiC_2).

SEST Observations

The SEST telescope has been used for several surveys of circumstellar CO emission in different kinds of samples, mainly to extend the observations to include southern objects. A survey of IRAS point sources in the IRAS two-colour diagram includes many kinds of evolved stars in different stages of their evolution, and many new detections have been made. Observations of a sample of bright carbon stars with well-known photospheric characteristics have made it possible to study the relation between photospheric properties, and those of the CSE. Of special interest is the detection of detached circumstellar shells, implying that the mass loss sometimes stops. A sample of S-stars was observed in order to study their relation to oxygen- and carbon-rich stars, and several new planetary nebulae have been detected.

Two surveys of SiO masers have been made, one of a sample of IRAS point sources, another of bright infrared objects. The detection rate was high in both surveys. Several individual southern objects have been studied in detail, among them the two supergiants VY CMa and VX Sgr, and the bright carbon star IRAS 15194-5115. In the latter, many molecules have been detected and its properties seem to be similar to IRC+10216, a well-known carbon star in the northern sky.

The individual programmes will now be described in more detail. Many of the projects are not finished and have been allocated more observing time during 1989, so the results are preliminary.

Observations of samples from the IRAS point source catalog. The project with the largest amount of allocated observing time is a joint ESO and Swedish project with 11 participants (Booth, Nyman, Carlström, Winnberg, Sahai, Habing, Heske, v.d. Veen, Omont, Forveille, and Rieu). It is a survey of circumstellar CO (J = 1-0) emission in a sample of totally 787 sources from the IRAS point source catalog, with the colour-colour characteristics described in the paper by van der Veen and Habing. The sources are all stronger than 20 Jy at 25 μm. The sample consists of all kinds of evolved stars, oxygen and carbon rich, Mira variables, OH/IR objects, PPN, and PN. Of these sources, 459 are situated in the southern sky, and the others will be observed with the Onsala 20 m telescope.

The idea is to build up a data base of circumstellar CO emission from stars at different stages of their evolution, to study mass-loss rates, chemistry, and other properties of the envelopes. Near infrared photometry of the sample is planned, and the stars will also be observed in the CO (J = 2-1) transition. So far, 215 objects have been observed with the SEST telescope, 88 objects have been detected, of which 54 are new detections. Objects with very cold CSEs, e.g. OH/IR objects and PPNs, are very weak in CO and sensitive observations are needed to detect them. Therefore, a special project to observe this type of objects was initiated together with the large survey. Several objects have been detected, among them a supergiant with an extremely wide line profile, almost 300 kms^{-1}.

Many evolved stars show strong SiO maser emission at 86 GHz. Haikala has made a search for SiO (v = 1, J = 2-1) masers from objects in the IRAS point source catalog with colour-colour characteristics similar to sources with already detected SiO maser emission.

The objects are mainly situated in the region of the colour-colour diagram of oxygen-rich sources with moderately thick CSEs (van der Veen and Habing, 1988). He observed 114 sources and found 53 new SiO masers. Since the SiO masers are variable in intensity, many of the non-detected sources would probably be detected, if they were observed at a later time.

Bright infrared sources. Le Bertre and Nyman have observed the SiO (v = 1, J = 2-1) maser emission from a sample of bright infrared sources, and made nearly simultaneous near-infrared observations. The sample consisted of 5 Mira variables, 2 supergiants, and 10 OH/IR objects. All sources, except 3 of the OH/IR objects, were detected in SiO. Previous attempts to detect this SiO transition in OH/IR objects have largely been unsuccessful (Nyman et al., 1986), maybe because of the large distance to many of these objects compared to Mira variables. In this sample of bright infrared sources (bright because they are nearby or intrinsically bright) there seems to be no difference in SiO intensity versus infrared intensity for the different types of sources.

Bright carbon stars. Olofsson, Eriksson, and Gustafsson have made CO observations of a sample of bright carbon stars (situated both on the northern and southern sky) with well determined photospheric characteristics, e.g. effective temperature T_{eff}, CNO abundances and $^{12}CO/^{13}CO$ ratio, giving a good opportunity to compare photospheric properties with those of the CSE. The first results have been presented in Olofsson et al. (1987) and Olofsson et al. (1988). In total, 32 stars were observed and 26 were detected of which 15 are new detections. A good correlation was found between the far infrared properties and mass-loss rates and also between the variability of the stars and their mass-loss rates.

One interesting result in this project is the discovery of three sources, S Sct (Fig. 1 by Olofsson), U Ant, and TT Cyg, with a peculiar double peaked CO line shape. A simple model of the CO emission from these objects shows that there is a distinct inner radius inside which little mass exists. The conclusion is that the mass loss has stopped, maybe because the star is experiencing a thermal pulse. The CO (J = 2-1) spectrum of U Ant also consists of a narrow parabolic profile which may indicate that the mass loss has recently recommenced in this source.

Olofsson, Eriksson, Gustafsson, and Carlström have observed HCN and $H^{13}CN$ toward the sources in the same sample to compare the HCN/CO abundance ratio in the photosphere with the same ratio in the CSE. This is interesting because in carbon stars HCN is thought to be of photospheric origin, while in oxygen-rich stars a photoinduced circumstellar chemistry is required to produce HCN. They detected 20 stars in HCN, and $H^{13}CN$ was seen only in the two ^{13}C rich stars in the sample. Due to the uncertainties in abundance determination, the preliminary result is that the HCN/CO abundance ratio is similar in the photosphere and the circumstellar envelope, in agreement with the chemical models.

S-stars, planetary nebulae, and supergiants. Sahai has made a survey of CO (J = 1-0) emission from S-stars to determine their mass-loss properties and compare them with oxygen-rich and carbon stars to test the hypothesis that the S-stars represent an evolutionary stage between the O- and the C-stars.

So far 15 objects have been observed and 4 new sources were detected, almost doubling the number of S-stars detected in CO. The proto type S-star π^1 Gru was mapped, it has an unusual asymmetric line pofile and an extended outflow.

Sahai, Wootten, and Clegg have made a search for CO (J = 1-0) emission from a large list of southern PN, detected 6 new sources and mapped 3 of them. NGC 6302 (Fig. 2) has a very interesting structure with at least 3 separate kinematic components. Sahai has observed two supergiants, VY CMa and VX Sgr, in CO. They both have very large outflow velocities. The CO profile of VY CMa is rectangular and almost point like in the CO map, implying that it is optically thin, which is surprising since the mass-loss rate determined from OH observations is very high. HCO^+ was also detected. The CO profile of VX Sgr is heavily contaminated by interstellar

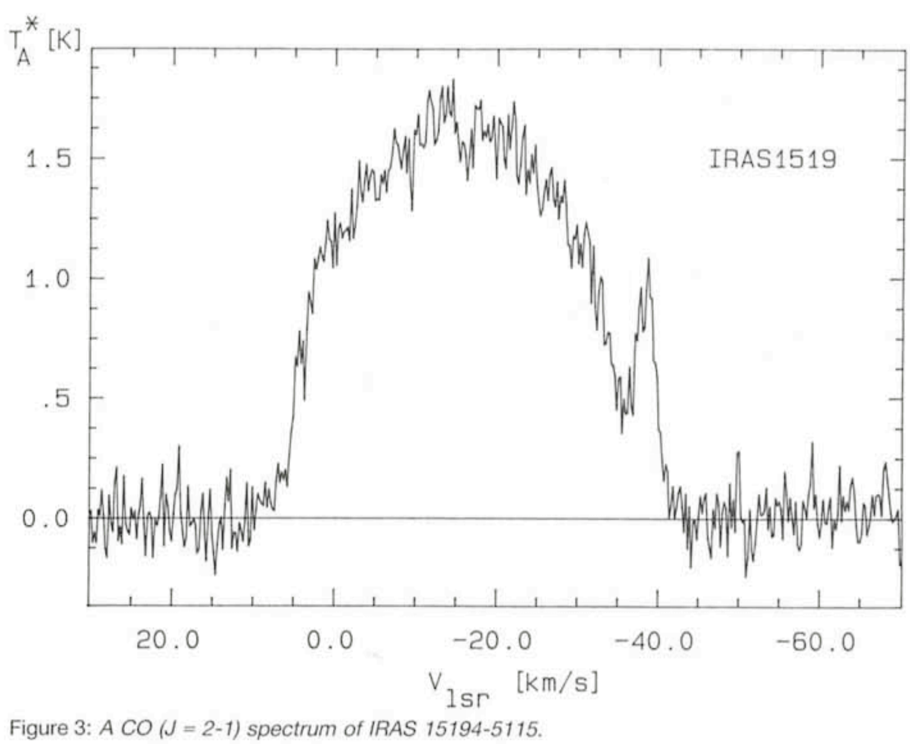


Figure 3: *A CO (J = 2-1) spectrum of IRAS 15194-5115.*

CO lines because it is situated in the Galactic plane. Further observations of all these projects are planned during 1989.

Molecular observations of a bright carbon star. The third brightest carbon star in the sky at 12 μm, IRAS 15194-5115, is located in the southern sky. It has properties similar to IRC + 10216 (the brightest carbon star and situated in the northern sky), which has a very well studied spectrum with many detected molecules. IRAS 15194-5115 is situated at a larger distance, however. Booth, Johansson, Nyman, Olofsson, and Wolstencroft have observed the IRAS source in many molecular transitions to compare it with IRC + 10216. CO, ^{13}CO, CS, HCN, HNC, HC_3N, C_2H, C_3H, C_4H, C_3N, SiS, and SiC_2 have been detected. The lines are about 10 times weaker than those in IRC + 10216 confirming the larger distance to the IRAS source, but the relative intensities of the molecular lines with respect to the CO (J = 1-0) line intensity are the same within a factor of two between the two sources. Figure 3 shows a CO (J = 2-1) spectrum of IRAS 15194-5115. Preliminary CO maps give a source size of 24″ (deconvolved with the beam) in the CO (J = 2-1) transition and 33″ in the CO (J = 1-0) transition.

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Molecular Clouds and Galactic Structure

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One of the features of the SEST is its sub-arcminute resolution, allowing one to observe molecular clouds at high spatial resolution, as described in a number of the other reviews in this issue. However, the SEST can also be used to investigate the large-scale distribution of the molecular cloud ensemble. Such a study, focused on the outer Galaxy, is the topic of this contribution.

Molecular clouds consist almost exclusively of H_2, which is, however, difficult to detect. CO is the next most abundant molecule in interstellar space, and it has easy-to-observe transitions in the mm-wavelength range. Because CO is primarily excited through collisions with H_2, it is possible to infer the distribution of the latter from that of CO.

The Outer Galaxy

The outer Galaxy, defined as those reaches of our system with galactocentric distances R larger than $R_\odot$ (= 8.5 kpc; the distance of the Sun to the galactic centre), has gained renewed interest as a region of study. From observations of H I emission it has become clear that at $R > R_\odot$ there are large-scale systematic deviations from a flat distribution (called 'warping') as well as a significant increase in the thickness of the gaseous disk (called 'flaring'). Such a morphology is in marked contrast to that of the inner Galaxy, where the atomic gas is confined to a disk of thickness ~250 pc (~120 pc for its molecular counterpart). The same phenomenon is seen in a number of other spiral galaxies, which in turn has stimulated astronomers to have a closer look at their own backyard. Almost all information on the distribution and motion of material at large R has come from observations of H I, mostly because all other "tracers" are confined to the inner Galaxy. It is important, however, to extend our knowledge of the outer Galaxy beyond what can be found from the 21-cm emission. We would like to know, for instance, the distribution and kinematics of the molecular material, an essential ingredient for the study of the influence of a changing galactic environment on star formation.

Much observational work, especially in CO, has already been devoted to the study of individual molecular clouds at $R > R_\odot$. But the larger scale picture suffers from incompleteness. Molecular clouds in the outer Galaxy are much more sparsely distributed than in the inner parts, and the intensity of the emission is generally low. Large-scale surveys, done on a regular grid, are out of necessity carried out with either severe undersampling or low sensitivity, and are in general confined to $|b| < 5°$. These constraints imply that many clouds, especially at larger distances, will be missed due to beam dilution, or due to the galactic warp.

IRAS sources

A representative view of the population of molecular clouds in the outer parts of the Galaxy can only be obtained if one knows where to look, such that the chance of detecting a CO emission line is high. In this way even a large telescope like the SEST can be used to derive the large-scale distribution of molecular gas. Jan Wouterloot (now at the University of Köln) and I searched for CO in the direction of a large sample of IRAS sources in the outer Galaxy, in a project started in September 1987 (when we used the SEST in test time, and we were both at the MPIfR in Bonn). These sources were selected from the IRAS point source catalog, on the basis of their colours, as having a high chance of being associated with regions of star formation. As all star formation takes place in molecular clouds, these IRAS sources act as flags for the location of the clouds in which they are embedded. A number of these IRAS sources are located close to optically visible H II regions, but many are not. The latter could be (ultra) compact H II regions, or be associated with a pre-main-sequence object.

In order to account for the galactic warp, the sources were selected in a latitude range between +10° and −10°. Initially the longitude range of the sample was chosen to be between 165° and 280°, and was later extended down to l = 85°, using the IRAM 30-m telescope.

Spatial Distribution

CO was detected towards 1077 (83%) of the 1302 sources selected in this way. We found CO emission towards these sources at velocities of (absolute values) up to 110 kms^{-1}. This is quite a difference with uniform-grid surveys, or surveys of optical H II regions, where very little emission, if any, is found at velocities in excess of 50 kms^{-1}. Using a rotation curve (i.e. the relation that gives the velocity of rotation around the galactic centre as a function of R, assuming all objects are in circular rotation), a kinematic distance could be derived for each CO emission component. In terms of distance, we found CO emission up to 15 kpc from the Sun, and out to R ≈ 20 kpc. In many cases more