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High-Resolution Spectroscopy of Evolved Stars: from ISO to HII/L2 †

By

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Abstract: The observations by the Short-Wavelength Spectrometer onboard the Infrared Space Observatory gave great impetus to the studies of AGB stars. The ISO/SWS has provided high quality, intermediate-resolution spectra covering a broad wavelength range of 2.4–45 μm. These data enable us, for the first time, to perform an extensive study of the outer atmosphere and inner circumstellar regions of AGB stars. Exploration of the undeveloped wavelength regions in the mid- to far-infrared has led to an enormous treasure of dust features. In this review, we particularly focus on the results of the ISO/SWS observations of O-rich objects. We then discuss the possible followup in future missions.

1. INTRODUCTION

The AGB (Asymptotic Giant Branch) is the last evolutionary stage for low- to intermediate-mass stars (1 $M_\odot \leq M_\star \leq 8\ M_\odot$). In this short period (of the order of 10^6 years), a star loses a significant fraction of its mass by ejecting the matter into the interstellar space, at a rate of 10^{-7}–$10^{-4}\ M_\odot\,yr^{-1}$. This "mass loss" phenomenon is the most important and interesting feature of AGB stars. The mass-loss process itself, its effects on the AGB evolution, and its contribution to the chemical evolution of the universe, have been studied intensively.

The generally believed mass-loss mechanism of AGB stars is as following: The AGB red-giants are mostly pulsating variables of Mira or semi-regular types. Stellar pulsations bring up the matter from the surface of the star and transport it gradually outwards. Farther out in the flow, gas cools down so that dust grains form. Subsequently, radiation pressure from the central star blows the dust along with surrounding gas out into the circumstellar envelope.

A star leaves the AGB when it exhausts hydrogen by nuclear burning and mass loss. The star shrinks by its gravity, and $T_{\rm eff}$ increases keeping almost the same luminosity. This evolutionary phase is called "post-AGB". Eventually, when the central star becomes hot enough,

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the gas in the envelope is ionized and excited by the high-energy photons from the central star. The envelope becomes visible as a planetary nebula. Observations of planetary nebulae show that the density distribution in the envelope is quite often aspherical, implying the presence of an equatorial disk (Balick 1987).

In this paper, we review the two most impressive and important discoveries made by the Short-Wavelength Spectrometer (SWS; de Graauw et al. 1996) onboard the Infrared Space Observatory (ISO; Kessler et al. 1996). Detections of various molecular features, some of which are totally unexpected, provide great clues to understand the pulsation dominated region between the stellar surface (photosphere) and the circumstellar envelope, the so called *extended atmosphere*. The discovery of the crystalline silicates in various evolved objects as well as young stars and comets opened a new field of astronomy, the *space mineralogy*. The formation mechanism of these crystalline dusts, the evolution of the host objects, and the evolution of the dust grains in space are discussed. Due to page limit, we focus on major topics of O-rich stars. Results of the ISO/SWS observations of C-rich stars are reported by, for example, Yamamura et al. (1998), Hron et al. (1998), Aoki et al. (1998, 1999), and Yamamura & de Jong (2000). As the summary of the paper we discuss what kind of observations are desired in future space missions in order to progress in these new field pioneered by the ISO/SWS.

2. MOLECULAR FEATURES IN AGB STARS

The nature of an AGB star is primarily determined by its C/O abundance ratio. Almost all available pairs of C and O atoms are locked in the very stable molecule CO, and only the reminder of either carbon or oxygen will further form other molecules and dominate the chemistry. In the oxygen-rich atmosphere, SiO, OH, H_2O, etc. are abundant, while CN, C_2, C_3, C_2H_2, and HCN are expected in carbon stars (Tsuji 1964, 1973). Figure 1 shows representative ISO/SWS spectra of O-rich and C-rich AGB red-giants with moderate mass-loss rates. In Figure 1, these species are clearly detected in R Cas (O-rich star) and R Scl (C-rich star). The C/O ratio also affects the dust composition. In oxygen-rich environment silicates are normally formed. Dust emission of amorphous silicates with some additional substructures — possibly by Al_2O_3 — is observed in R Cas. On the other hand, an emission peak of SiC grains is found in the carbon star, R Scl.

The detection of dioxide molecules, in particular, that of warm SO_2 gas in the atmospheres of AGB stars was a surprise. The ν_2 ro-vibration band at 7.3 μm is clearly detected in three stars out of 10 O-rich stars studied by Yamamura et al. (1999a) (Figure 2). We afterwards also found this band in the archived data of quite a few stars. This indicates that the phenomenon is rather normal in this type of stars. From a simple analysis using a *thermal slab* model, Yamamura et al. (1999a) concluded that the molecule is located at 2–6 $R_\star$ with a temperature of 600 K. Under thermal equilibrium state, the abundance of SO_2 molecule is negligibly small in the atmospheres of O-rich giants (Tsuji 1973). What ISO found was, however, that the molecule has to be very abundant. This fact implies that non-equilibrium chemical processes dominate the chemical structure in the extended atmosphere. Duari, Cherchneff, & Willacy (1999) showed that non-equilibrium chemistry in pulsation shocks influences the abundance of some molecules. For example, CO_2 (see below) abundance is enhanced. Beck et al. (1992) found that non-equilibrium chemical processes increase the SO_2 abundance significantly, if UV radiation from the central star is suppressed. Further detailed analyses based on the ISO results are urgently required.

Warm CO_2 gas of several hundred K appears both in the 4.3 μm and the 15 μm regions.

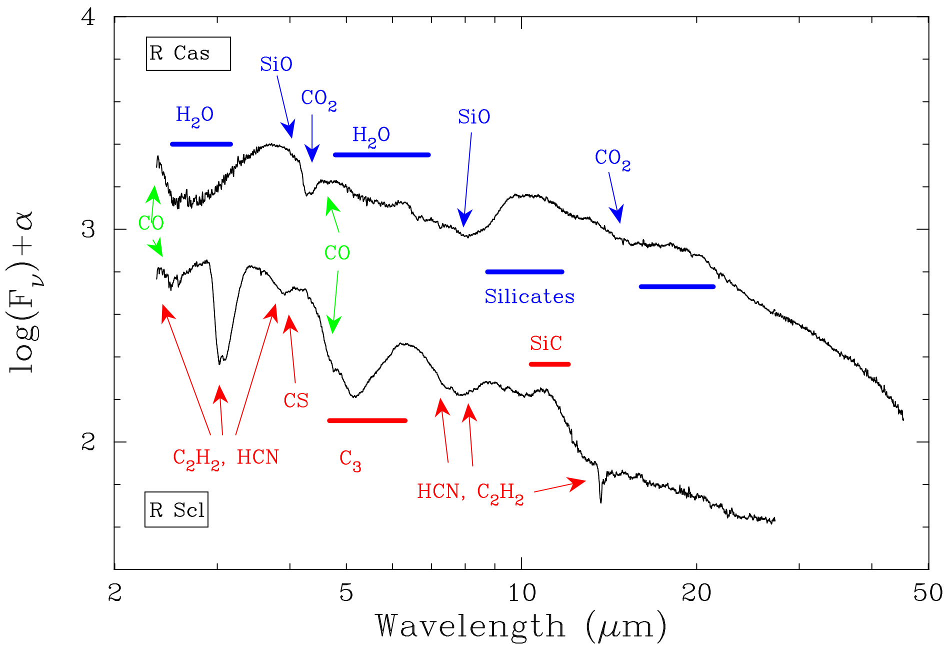

Fig. 1: ISO/SWS spectra of two AGB stars. The spectrum of the oxygen-rich star R Cas exhibits the molecular features of H_2O, SiO, CO_2, etc., while that of the carbon-rich star R Scl shows strong bands of carbon-bearing molecules such as C_2H_2, HCN, C_3 etc.

Especially interesting is the 15 μm region. Some O-rich stars with relatively low mass-loss rates exhibit satellite bands at 13.9, 15.4, 16.2 μm, etc. in addition to the fundamental band at 15.0 μm (Justtanont et al. 1998; Ryde et al. 1999). These satellite bands arising from excited vibrational levels are always seen in emission, in contrast to the fundamental band which is sometimes seen in absorption. The intensity ratios of the bands cannot be explained by a single temperature molecular layer. Using the thermal slab model, Cami et al. (2000) argue that the molecules are distributed in the extended atmosphere and in the circumstellar shell (say, $R \sim$ 4–10 $R_\star$) with temperatures in the range 100–700 K. Radiative pumping has been discussed by González-Alfonso & Cernicharo (1999).

Yamamura et al. (1999b) analyzed near-infrared H_2O bands in two Mira variables using the thermal slab model. They demonstrated that the observed spectra are satisfactorily fitted by two H_2O layers with temperatures of 2000 K and 1200–1400 K, respectively. Generally, the size of the H_2O layers is 1–3 $R_\star$: smaller than that of dioxide molecules. Sometimes, the 2000 K layer extends to as far as 2 $R_\star$ and the H_2O band is partly seen in emission. A detailed analysis of the near-infrared H_2O bands is in progress (Matsuura et al. 2000).

In Figure 3, we show the seven spectra of T Cep in the 2.3–5.3 μm region. The spectra in this range are dominated by an abundant molecule, H_2O. The shape of the H_2O bands seems to repeat (though not perfectly) after one cycle, i.e. the H_2O layers near the photosphere seem to follow the stellar pulsation. It is particularly interesting, on the other hand, that the time variation of the SO_2 feature in the same star T Cep does not correlate with the visual variability (Figure 2). In T Cep, SO_2 molecules are located at 4–6 $R_\star$ (Yamamura et al. 1999a). The band is seen in emission at the first minimum, while it is in absorption in the next minimum. Unfortunately, the ISO mission only covered 1.4 period of the star, and it is not clear whether

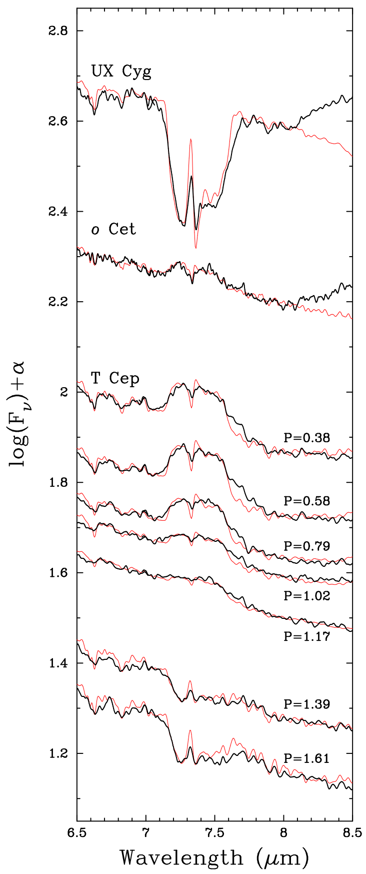

Fig. 2: The SO_2 ν_3 band in three O-rich Miras (*black* line). The band is seen either in emission or absorption. The spectra of T Cep show that the feature changes from emission to absorption in about one year, which is understood as the change of layer size and the column density. However, this variation *does not correlate with* the optical phase, which are indicated in the figure. A *thermal slab* model fits the observed features satisfactorily (*gray* line). This figure is taken from Yamamura et al. (1999a).

this variation is a transient phenomenon or it has a multi-periodicity of the pulsation cycle. Considering the fact that the dioxide molecules are located far from the central star whereas the H_2O band is formed within a few stellar radii, we conclude that the extended atmospheres in Mira variables can be divided observationally into two regions. The inner part ($R \lesssim 3$ $R_\star$) follows stellar pulsation, and the molecular abundances are explained by thermal equilibrium. In the outer region the variation does not follow the stellar pulsation anymore, and the non-thermal chemistry dominates the chemical structure. Time dependent chemical model in the extended atmosphere, including stellar pulsations and the dust formation, is a subject for future study.

3. SPACE MINERALOGY

Before the ISO mission, people believed that the dust grains in space are all amorphous. The observations by ISO revealed that this is not at all the case. Significant fraction of the silicates is found to be crystalline. The detection of crystalline silicates in evolved stars was

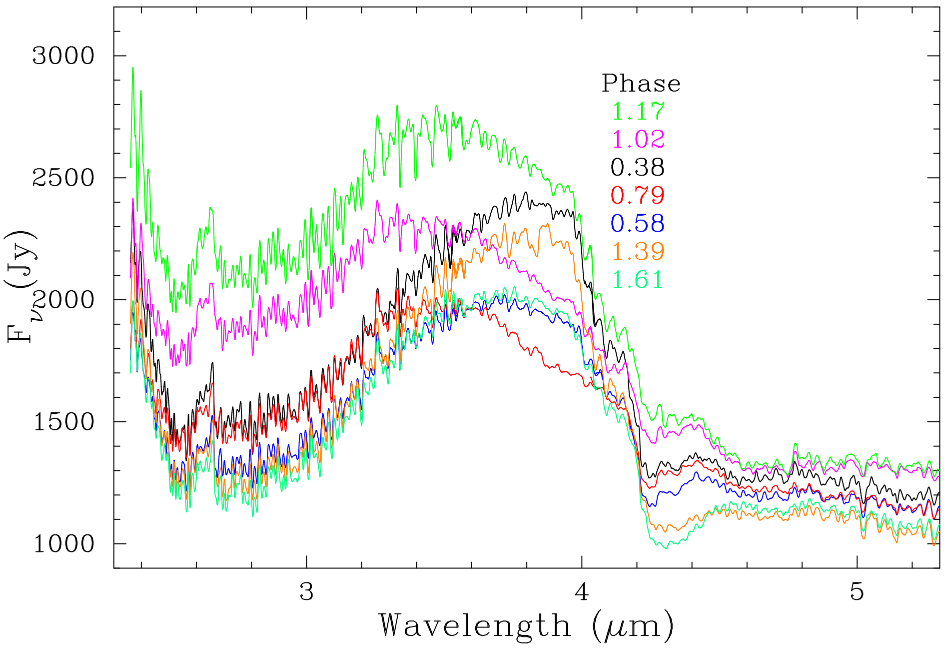

Fig. 3: Time variation of the SWS spectra of T Cep. The optical phases at the observations are indicated corresponding to the order of the spectra from top to bottom at 3.8 μm. The spectra in this wavelength region are dominated by the H_2O absorption band centered around 2.7 μm. The CO (4.6 μm and 2.3 μm), SiO (4.1 μm), and CO_2 (4.3 μm) bands are clearly detected. Sharp absorption lines between 3.0–3.5 μm are due to OH.

first reported by Waters et al. (1996). These objects show sharp peaks between 30 and 45 μm. Later studies show that more features in the wavelength as short as $\sim$ 15 μm and also in the LWS range, which are in contrast to the broad emission / absorption bands of amorphous silicates at 10 and 18 μm (Molster et al. 1999a; Silvester et al. 1999). Waters et al. showed that the features become more prominent as the objects evolve from AGB stars to planetary nebulae. It is now understood that this change of relative intensity of crystalline silicate features to the continuum emission is due to the decrease of the Rayleigh-Jeans radiation of hot amorphous dusts close to the central star. Detailed comparison of the ISO spectra with the laboratory measurements of the silicates (Koike & Shibai 1998; Jäger et al. 1998) confirmed the presence of both olivines ($Mg_{2x}Fe_{2-2x}SiO_4$) and pyroxenes ($Mg_xFe_{1-x}SiO_3$) in the objects. However, only those of Mg-rich are observed. The fraction of iron in these dusts is estimated to be less than 15 per cent (Molster et al. 1999a); i.e., Fe-contained dusts probably stay in the amorphous state. This selective crystallization seems to occur in any kinds of objects regardless age and the presence of disk or outflow. The formation process of the crystalline silicates in the mass-loss outflow is still unclear.

The presence of the crystalline silicate features directly indicates the presence of O-rich material. ISO revealed that many evolved objects whose central stars are known to be carbon-rich possess O-rich material. Figure 4 presents the SWS spectrum of one of such object, IRAS 09425−6040 (Molster et al. 2000). The spectrum up to $\sim$15 μm shows that the star is a "normal" carbon star, while the spectrum longward of that wavelength is dominated by the strong crystalline silicate bands. In fact, the object is the most crystalline-silicate-rich

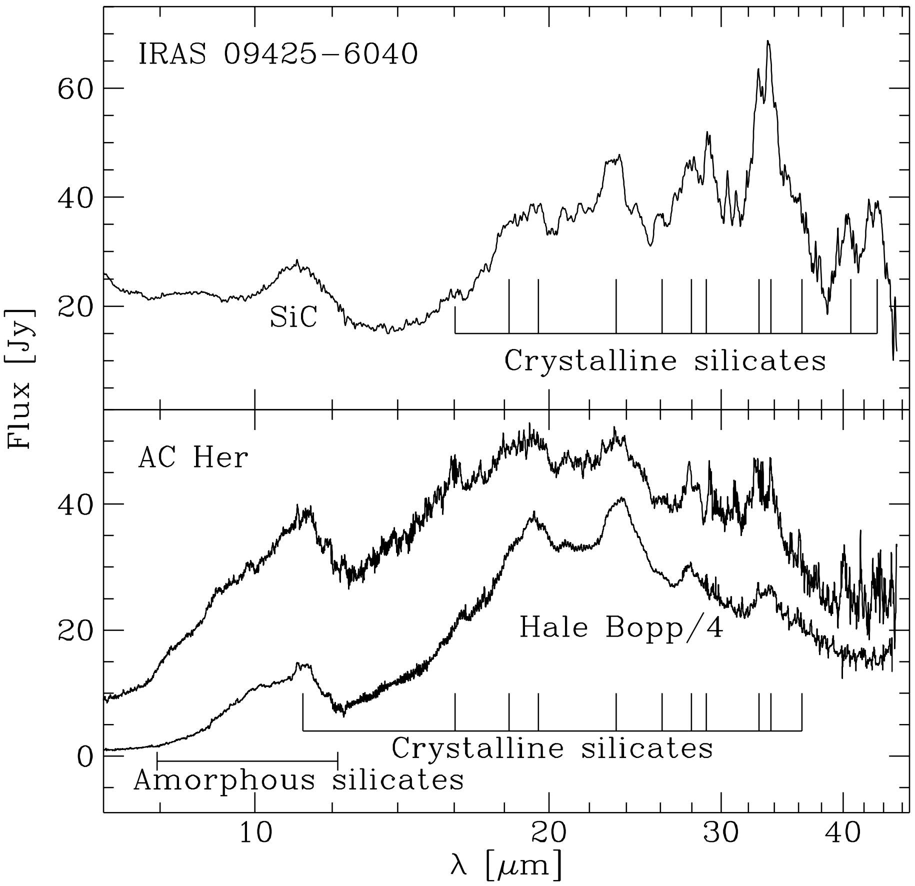

Fig. 4: *Upper*: The SWS spectrum of the carbon star IRAS 09425−6040. The star shows the most prominent crystalline silicate features of all the objects observed by ISO. About 75 per cent of silicates are crystalline. *Lower*: The SWS spectrum of the post-AGB object AC Her is compared with that of comet Hale-Bopp. The similarity of the two spectra is remarkable. The figure is taken from Molster et al. (1999b).

among those ISO has observed. Molster et al. estimated that about 75 per cent of the dust is crystalline. The high fraction of crystalline silicates is also found in another carbon-rich object, the Red Rectangle (Waters et al. 1998). The silicates in the carbon-rich objects must have been stored somewhere in the system when the objects were still O-rich. Direct imaging observations of the Red Rectangle showed that the silicates are likely stored in a massive equatorial disk. It is known that the Red Rectangle is a close-binary system with a period of 318 days (Waelkens et al. 1996). The disk was probably formed by the binary interaction while the central star was still O-rich. No direct evidence of a disk or binarity has been found in IRAS 09425−6040, but the similarity of the SWS spectrum with that of the Red Rectangle suggests that the star also has a circum-binary disk.

Crystalline silicate features are also detected in the disks of young stars (e.g. Malfait et al. 1998). The thermal annealing and the radial mixing in the disk (Shu, Shang, & Lee 1996) has been proposed for crystallization mechanism in such young systems. On the other hand, the binary-disk in the Red Rectangle and (probably) IRAS 09425−6040 should be cool (less than a few hundred K) and quiet, and thus no thermal annealing is expected. Molster et al. (1999b) suggested that in these stars athermal process must work to form crystalline silicates. Detailed studies of the mechanism should be carried out.

Even before ISO, comets have been found to have crystalline silicates, through the 10 μm region spectroscopies from the ground (Campins & Ryan 1989). The SWS spectrum of comet Hale-Bopp confirmed the presence of strong crystalline silicate features (Figure 4) everywhere in the SWS wavelengths range longer than 10 μm. It is noticeable that the spectrum is almost identical to that of the binary post-AGB star, AC Her. The similarity of these two spectra implies that the crystallization mechanism for these new and old objects are likely to be the same. Alternately, the dusts in comets originate from the evolved objects. Presently, it is not clear where the crystalline dusts in comets come from. They might be produced in the evolved stars, or they are recrystallized from scratch in the pre-solar disk. Unfortunately, the ISO/SWS was not sensitive enough to detect crystalline features in the interstellar medium. Such observations in future missions will be greatly appreciated.

4. SUMMARY

ISO/SWS spectra of evolved objects have significantly increased our understanding of these stars and their environments. The broad wavelength coverage is the greatest advantage of the ISO/SWS, which has enabled us to detect many unexpected features and to make a comprehensive study of the objects.

Detections of new molecular features in the spectra of AGB red-giants have progressed our knowledge of the extended atmosphere. With the SWS data, it is possible to test the model atmospheres in the infrared range. Especially those including dynamical (pulsation) effects (e.g. Höfner et al. 1998) are guided by the ISO observations. However, there is one important information for the studies of AGB atmospheres which ISO/SWS did not provide; velocity. Unfortunately, the resolution of the SWS is not enough to resolve the individual lines (line-width of, say, 3–5 $\mathrm{km\,s^{-1}}$), and thus what we observed was an integration through the atmosphere on the line of sight (and also over the spatial extent). Very high-resolution spectroscopies of AGB stars from the ground have shown that the data are useful to investigate the motion of the molecular layers as well as the possible abundance change during the pulsation cycle (e.g. Hinkle & Barnes 1979). These high-resolution spectroscopic observations should be extended to the wavelengths inaccessible from the ground, where the ISO/SWS assured the presence of important molecular features. To understand the variability of the extended atmospheres, periodical monitoring observations are essential. Our requirement for the instrument is;

- The resolution high enough to resolve the individual lines: $\lambda/\Delta\lambda \geq 10^5$;
- Broad wavelength coverage: e.g. λ =1–100 μm;
- Long life: stable for at least a few years.

AGB stars are very bright. However, to achieve such high resolution with the highest quality, 3.5 m or larger telescope are inevitably necessary.

Crystalline silicate features in the far-infrared wavelengths are only observed from space. For the observations, the resolution of 10^4 may be enough. Instead, very high sensitivity to detect (or to confirm non-detection of) the crystalline silicates in the interstellar medium is requested. Also, it is interesting to reveal the spatial distribution of the dusts around the stars.

Imaging spectroscopy would be a good challenge. In any case, a large aperture telescope is needed to achieve the sensitivity and the spatial resolution, especially in the longer wavelengths.

The analysis of the ISO/SWS spectra has just started. There are still a lot of things to do before proceeding to the new instruments. More complete model atmospheres are required. Studies of elemental processes such as non-equilibrium molecular chemistry and the dust formation processes are important. We especially stress the importance of the basic quantities of the molecules: complete and accurate molecular line list, collisional cross section for ro-vibrational transitions, etc. of as many molecules as possible. Laboratory measurements of the optical constants of the dust species are also encouraged.

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