THE PROMISE FOR AGB STARS: PHYSICS AND CHEMISTRY OF THE INNER CIRCUMSTELLAR ENVELOPE, AND THE MASS LOSS HISTORY

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Abstract

The Herschel HIFI heterodyne spectrometer and the PACS imaging/spectrometer instruments will provide important information on the physical and chemical conditions in the inner circumstellar envelopes of AGB-stars, e.g., on the rotational lines of the important coolants CO, HCN, and H_2O, and on various molecular species that participate in the initial chemistry of the escaping gas. Dynamical studies in the acceleration zone will be possible with HIFI, too. ISO was limited to high mass loss rate and/or very nearby objects and did not allow high resolution heterodyne spectra. Ground-based observatories cannot study most of the crucial far-infrared and sub-mm domains.

The solid state features of circumstellar dust particles are mainly found in the near- and mid-infrared ranges, although a crystalline water-ice feature at 62 μm has been seen towards early post-AGB objects, planetary nebulae, Herbig Ae/Be stars, and Herbig-Haro objects. Most ISO observations in these ranges were suffering from too low S/N-ratios. The sensitivity of Herschel is superior, but the short wavelength end of PACS may limit what can be achieved in this area.

The temporal variation of the mass loss rate is to a large extent unknown. This applies to all time scales from the pulsation period to the full time scale of the AGB-phase. Extended dust emission observed with PACS, perhaps in combination with Herschel-SPIRE, will provide important results on the long-term mass loss history.

Key words: Stars: variables: other – Stars: AGB – Stars: circumstellar matter – Stars: mass-loss – Radio lines: stars

1. Introduction

Extensive post-main sequence mass loss occurs for low and intermediate mass stars on the asymptotic giant branch (AGB; the large majority of all stars in the Universe that have left the main sequence will experience their final evolution as stars on the AGB), and for the higher mass stars during their red supergiant evolution. These winds affect the evolution of the stars profoundly, as well as the enrichment of the interstellar medium with heavy elements and grain particles. They also provide the starting conditions for the formation of planetary nebulae (PNe). The mass loss on the AGB is the by far the most well studied phenomenon, but the basic processes are still not understood or cannot be described in a proper quantitative way, e.g., the mass loss mechanism itself. These objects also provide us with fascinating systems, in which intricate interplays between various physical and chemical processes take place, and their relative simplicity in terms of geometry, density distribution, and kinematics makes them excellent astrophysical laboratories.

2. Inner parts of circumstellar envelopes

About 50 different molecular species have been detected at radio wavelengths, and an additional about 10 species in the infrared, in the circumstellar envelopes (CSEs) formed around low- and intermediate-mass stars during their final evolution as stars on the AGB. These CSEs provide wide ranges in density, kinetic temperature, and radiation environments, and the molecules are important probes of the great number of chemical and physical processes which take place in them.

Even though the boundary conditions are fairly well defined in CSEs much remains to be constrained observationally. Our present knowledge is mainly restricted by a lack of angular resolution, and too few lines observed per molecule to allow a proper modelling. Herschel observations can help in both these respects, despite its poor angular resolution.

Depending on chemistry and excitation requirements, the different molecules sample the conditions in different parts of a CSE. A particularly important molecule in this context is the density probe CO. Its different rotational transitions can be used to find the radial density structure, i.e., a mass loss archeology, despite the lack of enough angular resolution. For the case of a CSE formed by a mass loss rate of 10^{-5} $M_\odot$/yr the radii of the the maxima of the tangential optical depth of some CO transitions are shown in Tab. 1. All higher transitions are well observable with Herschel-HIFI!

Important to establish is also the temperature structure in the CSE. An important process here is line cooling in the inner parts of a CSE, and all the main coolants, CO and H_2O in O-rich CSEs and CO and HCN in C-rich CSEs, have a large number of lines within the frequency

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Table 1. Maxima of the tangential optical depth for a 10^{-5} $M_\odot$/yr mass loss rate object

Transition	Frequency	Maximum at
CO(1-0)	115 GHz	2×10^{17} cm
CO(5-4)	576 GHz	1×10^{16} cm
CO(10-9)	1150 GHz	2×10^{15} cm
CO(15-14)	1730 GHz	7×10^{14} cm

range of HIFI. These are also the most important cooling lines. Thus, we will be able to obtain data which can constrain our circumstellar models. Observations of many lines per molecule will be possible for essentially all of the lighter species detected at radio wavelengths, and this will provide good constraints for chemical models.

HIFIs high resolution spectra will allow studies of the dynamics of the innermost circumstellar zones, only a few stellar radii distant from the photosphere, where the final characteristics of the mass loss are determined. Probing with HIFI different parts of the CSE of objects with complex velocity structures and non-spherical geometries will allow to shed light on the detailed mass loss dynamics. Moreover, the light may be shed on the reason(s) for the very different typical geometries of AGB-CSEs and their successors, the envelopes around young post-AGB objects and PNe.

The chemistry in the inner CSE may be quite complex, including shock chemistry in a rapidly time variable environment and a possibility that the chemistry has an effect on the dynamics. Still there are reasonable boundary conditions, and we can expect to get important observational constraints on theoretical models by pursuing unbiased spectral scans of sources in different evolutionary stages and with different chemical compositions (in terms of the relative abundance of carbon and oxygen) (cf. Cernicharo et al. 2000).

An estimate of the detectivity can be obtained by examining the expected strengths of the CO rotational transitions J=5-4, 10-9, and 15-14, which lie at the ends and in the middle of the HIFI frequency range. We have used a radiative transfer program to obtain some preliminary values (Schöier & Olofsson 2001). For a well known, nearby, high mass loss rate C-rich object like IRC+10216 (with a $\dot{M}=1.5\times10^{-5}$ $M_\odot$/yr, and a distance of 120 pc) we get the intensities for Herschel-HIFI shown in Tab. 2.

Table 2. Intensities for IRC+10216

Transition	Intensity
CO(5-4)	7.5 K
CO(10-9)	7.2 K
CO(15-14)	6.3 K

Hence, such a source is easily observed with HIFI. To get an estimate of the observational space we have also calculated the expected intensities for two mass loss rates ($\dot{M}=10^{-6}$ $M_\odot$/yr and 10^{-5} $M_\odot$/yr) and one distance (1 kpc). The results are shown in Tab. 3. [We have assumed here that the CO molecules are exposed to a radiation field from a central blackbody of temperature 2500 K and a luminosity of 10^4 $L_\odot$. The results for the low mass loss rate object are somewhat dependent on this choice since radiative excitation plays a role close to the star.]

Table 3. CO line strengths for two CSEs located at a distance of 1 kpc

Transition	10^{-6} $M_\odot$/yr	10^{-5} $M_\odot$/yr
CO(5-4)	0.026 K	0.11 K
CO(10-9)	0.028 K	0.10 K
CO(15-14)	0.017 K	0.08 K

We conclude that a 10^{-5} $M_\odot$/yr source is reasonably easy to detect with HIFI at 1 kpc. However, on a moderate mass loss rate source (10^{-6} $M_\odot$/yr) observing time in excess of an hour is required to get good S/N-ratio at high enough frequency resolution. We can expect that all other molecular line emissions are comparable to or weaker than those of CO. Thus, with HIFI we are mainly restricted to sources in the solar neighbourhood. These are, on the other hand, objects which have been amply observed already, and where the Herschel data will provide very important complimentary information.

Complementing the work with HIFI discribed above, low resolution spectra delivered by PACS will extend the wavelength range down to ~60 μm and will have a much higher throughput (especially when compared to ISO, which was limited to high mass loss and/or very nearby objects).

3. MASS LOSS MINERALOGY

Most of the astronomical solid state features are found in the NIR and MIR ranges. ISO, especially with its SWS and LWS revolutionized our knowledge of dust and ice around stars. However, most of ISOs spectroscopic dust observations were really suffering from S/N-problems in all but the brigthest AGB stars. The sensitivity of Herschel would be crucial but the short wave-length end of PACS (~60 μm) is the clear limitation in this field!

Nevertheless an interesting crystalline water-ice feature has been observed at 62 μm in evolved AGB and young post-AGB objects, PNe, as well as in Herbig Ae/Be stars and Herbig-Haro objects (see e.g. Sylvester et al. 1999). Clearly this is also a “discovery area” for Herschel.

4. Mass loss history

The temporal variation of the mass loss rate is to a large extent unknown. This applies to all time scales from the pulsation period to the full time scale of the AGB-phase. On the intermediate time scales (10^2–10^4 yr) there is now growing evidence for substantial variations in the mass loss rate, e.g. detached CO and dust shells and multiple-shell structures seen in scattered light (Waters et al. 1994; Sahai et al. 1998; Mauron & Huggins 1999; Olofsson et al. 2000; Speck et al. 2000). There may be interrelations between the mass loss rate history and geometry.

Extended dust emission observed with PACS, perhaps in combination with Herschel-SPIRE, will provide important results on the long-term mass loss history. Two main strategies seem interesting: observations of spatially resolved nearby circumstellar envelopes, and surveys for fossile envelopes, i.e., the extended envelopes formed by long-term AGB mass loss, in different galactic and extragalactic environments.

4.1. Spatially resolved envelopes

For the nearest objects both PACS and SPIRE will deliver the detailed structures of the detached envelopes (resolving timescales of less than 1000 years). Even very low mass loss rate episodes will be detectable (including minor modulations)

At distances up to 1 kpc the largest shells are still more or less filling the field of view. All prototype detached shell objects known so far are found within a distance of about 500 pc: U Ant, U Cam, Y CVn, TT Cyg, U Hya, R Scl, and S Sct. These objects were detected in either in mm-CO or dust emission. PACS will resolve shells like these even at Galactic Centre distances!

4.2. Surveys for fossile envelopes

The influence of the environment on the AGB star evolution, especially the mass loss history, can be addressed by Herschel. We can judge the potential for searching for fossile envelopes by estimating the detectability of the known detached shell objects.

PACS will detect most detcahed shell objects in a given field of view at Galactic Centre distances at both 60 and 100 μm after only 10 min of integration. This allows e.g. surveys of the Bulge or areas of the central galactic plane in a relatively short time. This would nicely supplement ISO projects like ISOGAL.

PACS will reach the brighter detached shell objects even at the LMC distance after 2–3 hours on-source time. This allows an investigation of the effect of metallicity on the mass loss evolution. More normal high mass loss AGB stars can be detected in the Clouds after only a few minutes of integration using PACS or SPIRE.

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