Astrochemistry: From Molecular Clouds to Planetary Systems
IAU Symposium, Vol. 197, 2000
Y. C. Minh and E. F. van Dishoeck, eds.

ISO Observations of Solid-State Features in Circumstellar Disks

C. Waelkens,[1] K. Malfait[1] and L. B. F. M. Waters[2,1]

[1]*Instituut voor Sterrenkunde, Celestijnenlaan 200B, B-3001 Leuven, Belgium*

[2]*Astronomical Institute, Universiteit van Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands*

Abstract. ISO has opened new infrared windows for spectroscopy, enabling detailed studies of the composition of the dust particles present in circumstellar disks. For oxygen-rich dust, and in particular for silicates, a forest of new features has been discovered, and comparison with laboratory data has enabled the identification of most of them. Of special relevance is the detection of crystalline silicates, which present themselves as a new diagnostic for studying the formation of comets and planetesimals in the disks surrounding young and, surprisingly, also evolved stars.

1. Introduction: The Cosmic Dust Cycle

Cosmic dust is formed in the outflows of evolved stars, is processed during its long passage in the interstellar medium, and evolves quickly in the dense and shielded circumstellar disks which accompany the star-formation process. This symposium is essentially concerned with the latter phase, where circumstellar dust plays a major role in the formation of planetary systems. In order to understand in detail the relevant processes during this phase, it is, however, advantageous to situate them in the broader context of the cosmic dust cycle.

Dust formation requires an environment of sufficiently low temperature and high density. While supernova ejecta must account for a small fraction of the dust produced in the Galaxy, it appears that more than 90 percent of the galactic dust is formed in the outflows of the much more numerous and quieter outflows of AGB-stars, which represent the final evolutionary stages of low- and intermediate-mass stars.

The internal nucleosynthesis and dredge-ups in AGB stars, and the high binding energy of the relatively inert CO molecule, are decisive for the chemical composition of the dust particles which are formed in these events. Around M stars, whose photospheres preserve a C/O-ratio less than unity, virtually all C-atoms are locked in CO molecules, and an oxygen-rich chemistry develops, starting with corundum (Al_2O_3), and proceeding further to the formation of other oxides and silicates. Around C stars, where carbon has become more abundant than oxygen due to the dredge-up of freshly synthesised C-atoms, the chemistry follows a C-rich path, producing a rich variety of compounds, such as various carbides, amorphous carbon mixtures, graphite, and complex hydro-

https://doi.org/10.1017/S0074180900165003 Published online by Cambridge University Press

carbon chains and rings. Thanks partly to the vast literature on combustion processes, the carbon-rich chemistry relevant for astronomical environments is presently better understood than the oxygen-rich chemistry. For a relatively recent overview of the subject the reader is referred to the relevant papers in the proceedings of IAU Symposium 191 (Le Bertre et al. 1999).

By far the longest phase in the evolution of cosmic dust is its passage in the interstellar medium, where it is subject to the interstellar radiation field and to cosmic rays. That dust particles are able to survive this phase, is apparent from their major impact on interstellar extinction in the field and in molecular clouds. On the other hand, from the striking contrast between the large variety of dust features in circumstellar media with the rather homogeneous appearance of the extinction law, it is more than likely that significant dust processing occurs in the ISM.

As will be discussed in this contribution, the circumstellar media surrounding some newly formed stars display more spectral structure than typical molecular clouds, from which it appears that dust processing occurs in the dense and cool disks which are the remnants of the star-formation process. The evolution towards larger grains and macroscopic bodies may then rapidly result in the formation of planetesimals, and, at a slower pace, in that of planets (Lissauer 1993).

The possibility to obtain spectroscopy of cool environments over a large spectral range offered by the Infrared Space Observatory ISO (Kessler et al. 1996), and also the much increased power of ground-based infrared spectroscopy, have implied a significant increase of our potential to study observationally the circumstellar chemistry of young and evolved stars. A second important boost to the field has come from the recognition that direct analysis of interstellar and processed dust particles occurring in our solar system (see Gilmour and Messenger, this volume) provides important tests on circumstellar chemistry. It is certainly a gratifying circumstance that the stellar and solar-system communities re-discover their common interests, as this symposium attests. Last, but not least, the interpretation of IR spectra heavily relies on the laboratory experiments which are presently being performed by various groups (see Jaeger et al. 1998 and Ehrenfreund & Schutte, this volume).

2. Dusty Disks of Young Stellar Objects

Since molecular clouds are formed from the interstellar medium, in which the remnants from M- and C-stars have been thoroughly mixed, it is not surprising that both carbon- and oxygen-rich dust particles cohabitate in the circumstellar media of young stellar objects. Moreover, the destruction of CO molecules by the radiation of the emerging stars opens the possibility of new paths for the chemistry. Observations of C-rich molecules in such environments are discussed elsewhere (Tielens et al., this volume), so that this contribution essentially focuses on O-rich dust features, for which ISO has brought an impressive amount of non-anticipated new data on olivines ($[Mg/Fe]_2SiO_4$) and pyroxenes ($[Mg/Fe]SiO_3$).

Before ISO, it was thought that 'astronomical' silicates were essentially amorphous, producing distinctive broad features around 10 and 18 μm, both

https://doi.org/10.1017/S0074180900165003 Published online by Cambridge University Press

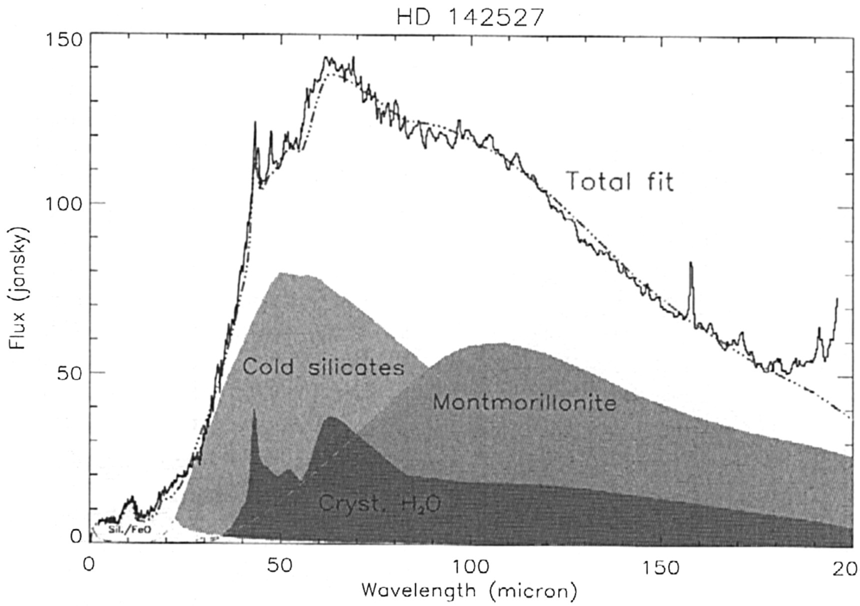

Figure 1. Model fit for the HD 142527 SWS-LWS spectrum with **MODUST**, a radiative transfer code developed by de Koter & Bouwman (2000).

being accessible to ground-based observations. Interestingly, well documented pre-ISO evidence exists for peculiar 10 μm features for early-main-sequence stars with remnant disks, such as β Pictoris (Knacke et al. 1993) and 51 Ophiuchi (Fajardo-Acosta et al. 1993), similar to those observed in certain comets, such as P-Halley (Campins & Ryan 1989; Herter et al. 1987) and Comet Levy 1900 XX (Lynch et al. 1992), pointing towards the presence of a crystalline variety of silicates, and confirming the hypothesis that cometary objects orbit these stars in huge quantities (cf. Ferlet et al. 1993).

Peculiar 10 μm features are now well documented in ground-based IR spectra of several young stars (e.g. Hanner et al. 1998). It was ISO, however, which disclosed the full richness of the crystalline silicate spectra in the 20 to 80 μm region, and, interestingly, both in evolved as well as young stars (Waters et al. 1996; Waelkens et al. 1996). These results have triggered new efforts in laboratory astrophysics (Jaeger et al. 1998; Koike & Shibai 1998) from which it appears that a reliable identification in terms of different olivines and pyroxenes is possible, but only so if a broad spectral range is observed.

The richness of the ISO spectra is illustrated in Figures 1 to 3. The objects shown in Figures 1 and 2 both are 'isolated Herbig Ae/Be stars', i.e. young stellar objects with masses exceeding two solar masses, which are not obviously linked to a star-formation region. The young nature of these objects follows from their huge IR excesses, from the presence of emission lines in their optical spectrum and from their location in a Hipparcos-based HR-diagram (van den Ancker et al. 1998). It is not clear, however, whether the isolated nature should

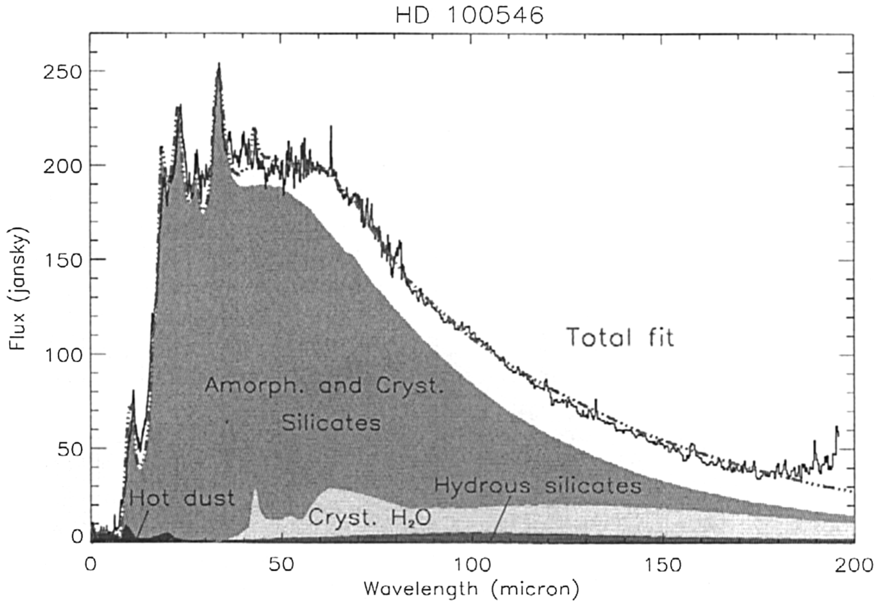

Figure 2. Model fit for the HD 100546 SWS-LWS spectrum with **MODUST**; the resulting dot-dot-dot-dashed line represents the sum of the warm and the three cold dust components.

be viewed as an argument for an appreciable age, or alternatively as an argument for the occurrence of an isolated mode of star formation: the Hipparcos age of HD 100546 is consistent with it being a 5 Myr-old main-sequence star, but HD 142527 occurs close to the stellar birthline! By all means, the isolated nature of these objects is advantageous for the interpretation of their IR spectra, since these are not affected by contributions from a molecular cloud in which they would be embedded. From the objects shown in Figure 3, HD 179218 may also be considered as an isolated Herbig Ae/Be star, while the nature of the more massive object HD 45677 remains controversial (Bopp 1993; de Winter & van den Ancker 1997; Lamers et al. 1998).

The spectrum of HD142527 has been discussed in detail by Malfait et al. (1999). For this object ISO-spectra obtained with both the Short-Wavelength Spectrometer SWS (de Graauw et al. 1996) and the Long-Wavelength Spectrometer LWS (Clegg et al. 1996) could be combined, and it appears that this combination is essential for a reliable interpretation. A dominant component of the IR flux stems from crystalline water ice (50 percent in mass), from cold amorphous silicates (35 percent) and from layered hydrous silicates (15 percent), which were modeled with the available optical constants of a particular mineral called montmorillonite (Koike & Shibai 1990). While the attribution to a particular mineral is hazardous, and was only done on the basis of the availability of laboratory data, the relevant result to note is that the broad shoulder present around 100 μm points to a silicate with water inclusions. In this framework it is interesting to note that a long-standing controversy exists in the meteoritic society whether the presence of water-ice inclusions in some meteorites is intrinsic or has been acquired on Earth (Gilmour, these proceedings). A controversy also exists on whether the presence of crystalline water in some comets reflects their original composition or is rather due to processing during earlier passages close to the Sun. The presence of both kinds of compounds in the cold and young disk of HD142527 then in both cases argues for the former hypothesis.

The spectrum of HD100546 has been discussed by Malfait et al. (1998), who pointed out the striking similarity of its silicate features with those of Comet Hale-Bopp (Crovisier et al. 1997). The modelling presented in Figure 2 is - as for HD142527 in Figure 1 - the result of a radiative-transfer calculation with the MODUST programme (de Koter & Bouwman 2000). From the presence at 69 μm of the longest-wavelength silicate feature, which is very sensitive to the Mg/Fe ratio, it follows that forsterite, i.e. pure-Mg olivine, is present around this star, and that this particular mineral is responsible for nearly all sharp emission features in the spectrum. From the modeling it follows also that the amorphous silicate component is Mg-rich, and that iron preferentially occurs in its metallic form and in FeO grains.

Unfortunately, for HD45677 and HD179218 only SWS spectra are available, and the lack of information at longer wavelengths hampers a unique interpretation of the rich IR spectra these objects display (Figure 3). Although the nature of both objects is perhaps completely different, a striking similarity is seen in the spectra. The features that are seen in one spectrum, are recovered in the other one as well, nearly without exception. Most of the features which occur can be ascribed to various olivine and pyroxene species, the latter both with orthorhombic and the rather unusual monoclinic crystallographic structure. The most likely identification of their common 21 μm emission feature is in terms of quartz (SiO_2, Henning & Mutschke 1997).

The disks of young stellar objects are relatively faint infrared sources, and only a handful of them could be observed with ISO at the signal-to-noise ratio their complex spectra require. The higher sensitivity of SIRTF will certainly enable a statistically more relevant sample to be discussed. On the other hand, it is clear that not only sensitivity but also spectral coverage is a determining parameter for a detailed composition analysis, so that more ambitious future infrared space missions are highly desirable.

3. Evolution and Processing

It has been a most fortunate circumstance that the ISO satellite was operational when the brightest and most dusty comet since decades appeared in the sky. The striking similarity between the spectra of HD100546 and Comet Hale-Bopp, dominated in both cases by crystalline forsterite, strongly suggests that certain young stars have been observed during a phase similar to the early phase of our solar system, i.e. when planetesimals and comets were abundantly present. Detailed information on cometary material can also be obtained from laboratory studies of interplanetary dust particles (IDPs) collected by stratospheric flights (Messenger, this volume), if these indeed originate from comets. An immediate warning is, however, that such studies evidence the fluffy structure of IDPs,

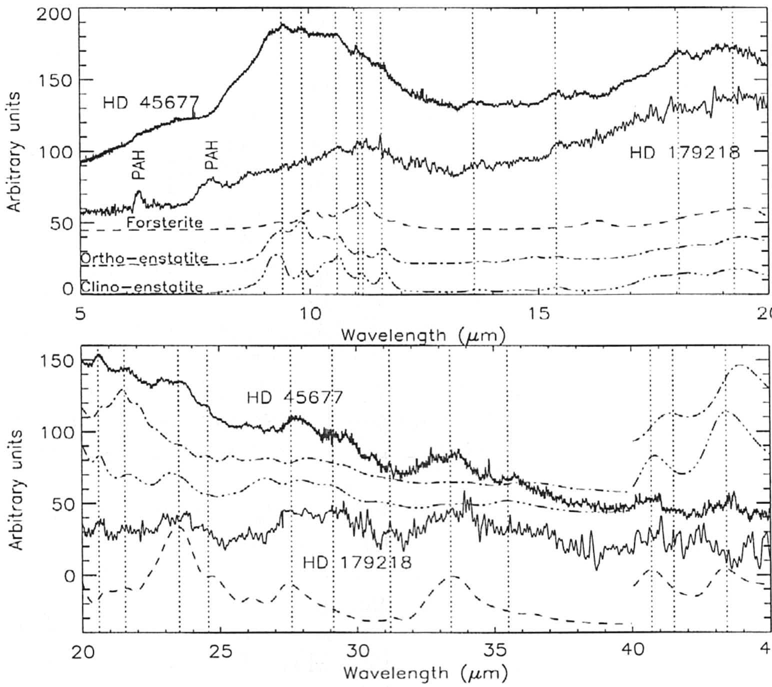

Figure 3. Comparison between the SWS-spectra of HD 179218 and HD 45677 (the y-axis is scaled arbitrarily). Overplotted are the absorption efficiencies of forsterite (dashed), ortho-enstatite (dot-dashed) and clino-enstatite (dot-dot-dot-dashed) (Koike et al. 1993). Longwards of 40 μm, the absorption features have been multiplied by an arbitrary factor for visualisation purposes.

while the modeling of IR spectra still relies on simple spherical or ellipsoidal particle geometries.

It should also be pointed out that no simple one-to-one relation appears to exist between the evolution of particular stars and their dust disk. Studies of clusters demonstrate that huge differences exist between the IR properties of pre-main-sequence stars of the same mass and age: similar stars where one has an important IR excess and the other none do coexist (e.g. Perez et al. 1987). It is indeed likely that dynamical interactions between stars are efficient in removing disks. Also for isolated Herbig Ae/Be stars there does not appear to be an obvious correlation between the age of the star and the disk mass, HD100546 being one of the most evolved such objects and apparently the brightest one in the infrared.

The necessary precautions being made, it does appear, however, that crystalline silicate spectral fingerprints are not visible in the spectra taken from the youngest objects. Thus, the crystallization process can be linked with a more advanced evolutionary stage of the disk, presumably that when planetesimal

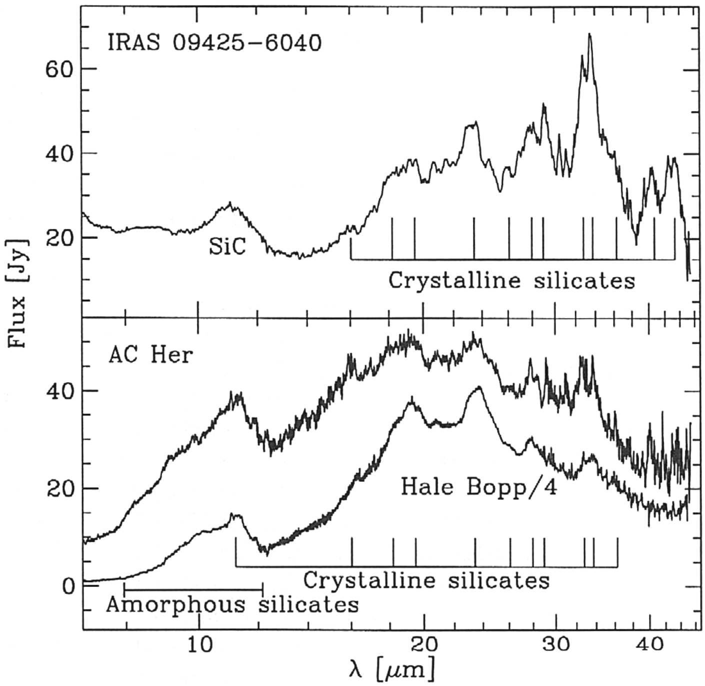

Figure 4. ISO-SWS spectra of the evolved objects IRAS 09425-6040 and AC Her. The former object is the source for which the crystalline silicate bands are most prominent, accounting for 75 % of the observable dust mass; the spectrum of the latter object presents the best match with the SWS spectrum of Comet Hale-Bopp.

formation is already well advanced. The silicate spectra of the youngest, still partially embedded sources consistently appear amorphous or with at most modest crystalline contributions (e.g. AB Aurigae, HD162396; van den Ancker et al. 2000), and sources such as HD100546, for which crystalline silicates are abundant, are definitely evolved. Moreover, the occurrence of crystalline forsterite in HD100546 over the large temperature range from 220 to 50 K suggests that the processes dispersing the comets to large distances from the star are presently operating in this system, thus indirectly suggesting the presence of the giants planets which are thought to be dynamically responsible for the formation of an Oort Cloud (Fernandez 1978).

4. Crystalline Silicates: also in Evolved Stars!

As mentioned in the introduction, crystalline silicate features in ISO spectra were also detected for AGB and post-AGB stars (Waters et al. 1996). Subsequent studies have revealed that in some evolved objects these features are fairly strong. It now appears that, while weak features are observed in the dense outflows of some luminous evolved stars for which no evidence for binarity exists (Waters et al. 1996), crystalline silicates are most prominent around binary objects, and occur there in long-lived circum-binary disks.

A remarkable example is the famous Red Rectangle nebula, which is the prototype of a class of carbon-rich reflection nebulae surrounding low-mass stars in the final stages of evolution. While the near-IR spectrum of this object is dominated by PAH features in the extended nebula, its 20–40 μm spectrum (Waters et al. 1998) is characterized by crystalline oxygen-rich emission bands which originate in the disk known to surround the central binary (Roddier et al. 1995; Van Winckel et al. 1995; Jura et al. 1995). A second example is the more massive binary system AFGL4106 (Molster et al. 1999a).

In Figure 4, the ISO-SWS spectra of the carbon-rich giant star IRAS09425-6040 and of the RV Tauri-type variable post-AGB star AC Herculis are shown (Molster et al. 1999b). Direct evidence for binarity only exists so far for the latter object (Van Winckel et al. 1998), but the resemblance of the spectrum of the former to that of the Red Rectangle, and in particular the coexistence of C-rich and O-rich dust, strongly argues for the binarity of IRAS09425. It certainly is an amazing fact that the object for which the ISO spectrum most resembles that of Comet Hale-Bopp is the evolved star AC Herculis!

It is then tempting to conclude that the ISO spectra of these evolved objects suggest that the processes which initiate planet formation also occur in the disks surrounding these evolved stars, thus implying that planet formation is a most natural process in circumstellar disks. While the spectral diagnostics are indicative of comet and/or planetesimal formation only, the presence of a density contrast in the disk of the Red Rectangle has been interpreted as evidence for the occurrence of a giant planet (Jura et al. 2000).

The observations that crystalline silicates are not seen in the disks of the youngest stars and, for evolved stars, are most prominent in the long-lived disks surrounding binary systems, suggest that time is a critical parameter for the crystallization of silicates to occur. However, if crystallization is the result of thermal annealing, as laboratory experiments suggest (Hallenbech & Nuth 1998), the typical temperatures prevailing in the disks would imply timescales for annealing which are prohibitively large. While it may be possible that the processing in the disks of young stars involves outwards migration of grains after a passage in the warm environment close to the star, such a hypothesis seems most unlikely for the evolved binary systems, so that it may be concluded that the crystallisation process itself is presently not understood.

Acknowledgments. CW and KM acknowledge financial support from the Fund of Scientific Research - Flanders, from the Belgian Federal Services for Scientific, Technological and Cultural Affairs and from the Research Council of the K.U. Leuven. LBFMW acknowledges financial support from an NWO Pionier grant.

References

Bopp, B.W. 1993, Inf. Bull. Variable Stars, 3834
Campins, H. & Ryan, E.V. 1989, ApJ, 341, 1059
Clegg, P.E., et al. 1996, A&A, 315, L38

Crovisier, J., et al. 1997, Science, 275, 1904
de Graauw, M.S., et al. 1996, A&A, 315, L49
de Koter, A. & Bouwman, J. 2000, in preparation
de Winter, D. & van den Ancker, M.E. 1997, A&AS, 121, 275
Fajardo-Acosta, S.B., Telesco, C.M., & Knacke, R.F. 1993, ApJ, 417, L33
Ferlet, R., et al. 1993, A&A, 267, 137
Fernandez, J.A. 1978, Icarus, 34, 173
Hallenbeck, S. & Nuth, J. 1998, Ap&SS, 255, 427
Hanner, M.S., Brooke, T.Y., & Tokunaga, A.T. 1998, ApJ, 502, 871
Henning, T. & Mutschke, H. 1997, A&A, 327, 743
Herter, T., Campins, H., & Gull, G.E. 1987, A&A, 187, 629
Jaeger, C., et al. 1998, A&A, 339, 904
Jura, M., Balm, S.P. & Kahane, C. 1995, ApJ, 453, 726
Jura, M., et al. 2000, Nature, in prep.
Kessler, M., et al. 1996, A&A, 315, L27
Knacke, R.F., et al. 1993, ApJ, 418, 440
Koike, C. & Shibai, H. 1990, MNRAS, 246, 332
——— 1998, ISAS report no. 671
Koike, C., Shibai, H., & Tuchiyama, A. 1993, MNRAS, 264, 654
Lamers, H.J.G.L.M., et al. 1998, A&A, 340, 117
Le Bertre, T., Lebre, A., & Waelkens, C. 1999, Asymptotic Giant Branch Stars, IAU Symposium 191 (ASP Conference Series)
Lissauer, J.J. 1993, ARA&A, 31, 129
Lynch, D.K., et al. 1992, Icarus, 100, 197
Malfait, K., et al. 1998, A&A, 332, L25
Malfait, K., et al. 1999, A&A, 345, 181
Molster, F.J., et al. 1999a, A&A, 350, 163
Molster, F.J., et al. 1999b, Nature, 401, 563
Perez, M.R., Grady, C.A., & The, P.S. 1987, PASP, 99, 1050
Roddier, F., et al. 1995, ApJ, 443, 249
van den Ancker, M.E. 1998, A&A, 324, L33
van den Ancker, M.E., et al. 2000, A&A, in press
Van Winckel, H., Waelkens, C., & Waters, L.B.F.M. 1995, A&A, 293, L25
Van Winckel, H., et al. 1998, A&A, 336, L17
Waelkens, C., et al. 1996, A&A, 315, L245
Waters, L.B.F.M., et al. 1996, A&A, 315, L361
Waters, L.B.F.M., et al. 1998, Nature, 391, 868

Discussion

P. Ehrenfreund: Could you explain more details of the idea of low temperature crystallization in long-lived disks? How do you extrapolate from existing laboratory data?

C. Waelkens: Laboratory data show that crystallization occurs easily at temperatures above 1000 K. But that the efficiency of the process drops very fast with decreasing temperature. Extrapolation of these data would imply temperatures above 800 K for the timescales relevant to these disks. At the low temperature that are observed (below 300 K) timescales of thousands of Hubble times would be necessary ...

S. Saito: Many people tried to detect gaseous FeO spectral lines, but all efforts were not successful. It is very exciting that Fe and FeO were detected in solid grains. Is it possible to estimate the quantity of Fe and FeO in the souce observed?

C. Waelkens: So far, spectral evidence for metallic Fe and for FeO comes only from the warm component of the dust, which amounts to a mass fraction which is rather marginal. But there is no reason why these species could not also occur in the cooler dust, where they are not easily detected in our spectra. In this context, it is certainly significant that the silicates are largely Mg-rich. The iron must be somewhere, and then the near-IR results suggest that it is in the form of metallic Fe or FeO.

https://doi.org/10.1017/S0074180900165003 Published online by Cambridge University Press