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On the origin of the 19.5 μm feature

Identifying circumstellar Mg-Fe-oxides★

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Abstract. We report the detection of a broad, prominent 19.5 μm dust emission feature in ISO-SWS spectra. It is especially conspicuous in the spectra of low mass-loss AGB stars belonging to the variability classes SRb and Lb with relatively high photospheric temperatures. The feature carrier is proposed to be $Mg_{0.1}Fe_{0.9}O$, a solid solution of MgO (periclase) and FeO (wustite). This dust species has cubic crystal symmetry like spinel, the carrier of the 13, 16.8 and 31.8 μm spectral features, together with which the 19.5 μm feature is being observed. A broad emission plateau between 11 and 15 μm, which is attributable to amorphous Al_2O_3, is also detected together with the 19.5 μm and the spinel features. As a consequence of our discovery, we postulate the existence of a distinct class of circumstellar shells, dominated by oxide and not by silicate dust.

Key words. stars: circumstellar matter – stars: formation – stars: AGB and post-AGB – solar system: formation – methods: laboratory

1. Introduction

In the outflows of oxygen-rich Asymptotic Giant Branch (AGB) stars, mainly silicates and oxides are forming. Some observational evidence for a non-silicate component in oxygen-rich circumstellar dust shells was yielded already by ground-based observations (e.g. Hackwell 1972) and by the Infrared Astronomical Satellite (IRAS), which seemed to deliver indications for the presence of aluminium oxide dust (Onaka et al. 1989).

Iron monoxide (FeO) has been postulated to be a component of interstellar dust some 25 years ago by Duley & Millar (1978). Only in the 1990s, indirect observational evidence for the existence of circumstellar iron-containing oxides was found: atomic Fe turned out to be strongly depleted in Post-AGB-stars (see e.g. Rietmeijer 1992). A detailed laboratory investigation of Mg-Fe-oxides has been published by Henning et al. (1995), who also derived the sets of optical constants on which the present paper is based. It has been pointed out by these authors as well as by Begemann et al. (1995) that an enhanced 20 μm emission in the spectra of cool stars would be an indication for Mg-Fe-oxide formation. Bagnulo & Doyle (1997), presenting ground-based observations made in the *Q* band, delivered new evidence for such an enhanced 20 μm emission and proposed a Mg-Fe-oxide to be its carrier.

The Infrared Space Observatory (ISO) made it possible to study the mineralogical composition of dust ejected by AGB stars in great detail. The expectation of the pre-ISO era that circumstellar dust is amorphous was shown to need thorough revision due to the detailed studies of crystalline silicates by Jäger et al. (1998), Molster (2000) and others.

Thermodynamical calculations on mineral formation in stellar winds (e.g. Gail 1998) show that pure FeO is probably not among the primary condensates in stellar outflows due to its low condensation temperature. Condensation experiments with a Mg-Fe-SiO-H_2-O_2 vapour by Rietmeijer et al. (1999) did not deliver any evidence for the formation of mixed Mg-Fe-oxides. However, both results do not necessarily preclude the possibility of Fe diffusion into previously condensed MgO.

In the present paper, we show that a broad emission feature peaking at a wavelength of 19.5 μm and especially prominent in the spectra of low mass-loss AGB stars is most probably due to an Fe-rich solid solution of MgO and FeO. Both the position and the width of this feature are in excellent agreement with the diagnostic spectral characteristics of small, spherical particles of $Mg_{0.1}Fe_{0.9}O$.

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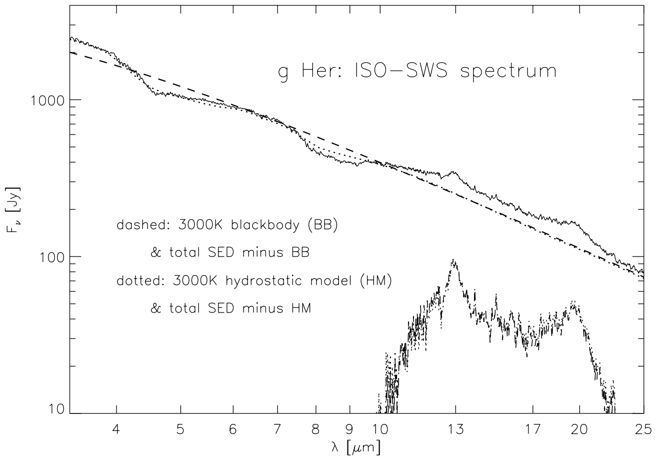

Fig. 1. ISO-SWS spectrum of g Her in the 5–25 μm range compared to a blackbody fit and a hydrostatic model fit (both for an assumed photospheric temperature of 3000 K).

2. Major sources and accompanying spectral features of the 19.5 μm emission band

In the open time ISO projects `fkerschb.orichsrv/orichsrl/zzagb2pn` and `jhron.varlpv/varlpv2`, attention has been paid, among others, to oxygen-rich variables on the AGB with high photospheric temperatures (near 3000 K) and low mass-loss rates (in the order of 10^{-7} $M_\odot$/y). Many of these stars are Semiregular Variables of the type SRb. A rather surprising result of the spectroscopy performed with ISO-SWS in this context is that there do exist stars with very little silicate emission, but distinct emission bands at 13, 16.8, 31.8 and 19.5 μm plus an emission plateau between 11 and 15 μm.

Figure 1 shows an example of a star (g Her) with a dust spectrum dominated by the emission bands at 13 and at 19.5 μm. The 10 and 18 μm silicate emission bands characteristic of amorphous silicates are almost completely missing in this case. Note that a "pseudo-silicate emission" band at 10 μm is produced by the photospheric SiO molecular *absorption* trough between 7.5 and 9.5 μm. This is demonstrated by comparison with a photospheric model (dotted line) taking into account the molecular absorption.

The 13, 16.8 and 31.8 μm features have, after reduction of additional spectra from the ISO archive and detailed laboratory studies of Mg-Al-oxides, been attributed to $MgAl_2O_4$ (Fabian et al. 2001). The 19.5 μm band, by contrast, has not yet been definitely identified. We even suspected that it could be an instrumental artifact since it is centered very close to the border of the ISO-SWS bands 3C and 3D. This assumption, though, proved erroneous: the 19.5 μm feature is also seen in ground-based observations of EP Aqr and other stars (see Bagnulo & Doyle 1997), whereas it is, on the other hand, absent from the ISO-spectra of dust-free stars (like Arcturus or Aldebaran) as well as from carbon-rich stars. An additional proof for the reality of the 19.5 μm band is the presence of a very similar one (centered at 19.7 μm) in IRAS-LRS spectra (see Goebel et al. 1989).

Table 1. The sample of stars in which we detected a particularly strong 19.5 μm emission feature. The values in the last column indicate the observed positions of the band attributed to an Mg-Fe-oxide.

GCVS	IRAS name	type	P [d]	ML	λ [μm]
Y UMa	12380+5607	SRb	168	1.5	19.5
θ Aps	14003–7633	SRb	119		19.5
RX Boo	14219+2555	SRb	340	5	19.5
g Her	16269+4159	SRb	89	1	19.5
V1943 Sgr	20038–2722	Lb		1.3	19.5
EP Aqr	21439–0226	SRb	55		19.6
SV Peg	22035+3506	SRb	144	3	19.4

Even if the reality of the 19.5 μm feature seems incontestable, it is a nontrivial task to derive its profile, because the bandwidth is so large that an isolation from other (oxide and silicate) dust emission components is difficult. For those stars which seem to have an especially small silicate dust emission (g Her, Y UMa and V1943 Sgr), we derived the dust emission spectra by subtracting a photospheric model SED. This model SED takes account molecular absorption due to CO, H_2O and SiO (see Aringer et al. 2002). However, it does not take into account emission from the outer atmosphere (if present). It has been assumed that at 7 μm, the spectrum is entirely dominated by stellar radiation and that the dust emission vanishes at this wavelength. The resulting normalized dust emission profiles are shown in Fig. 2.

Apart from the 19.5 μm band, the following spectral features are clearly visible: the sharp 13 μm band, even sharper molecular CO_2 lines at 13.87, 14.97 and 16.18 μm (Justtantont et al. 1998) and, finally, a very broad underlying "continuum emission" peaking around 11 μm and dropping off very slowly in the 12–15 μm range. This very broad dust emission is attributable to amorphous Al_2O_3, the optical constants of which have been published by Begemann et al. (1997). Apart from the elsewhere analysed spinel features at 13 and 16.8 μm, the dust emission of g Her, V1943 Sgr and Y UMa is surprisingly well reproduced by oxide dust only. It is not necessary in these cases to assume the presence of silicate dust. Note that it does not seem as if there were a strict correlation between the strengths of the 13 and 19.5 μm emission bands, which makes it unlikely that both have the same carrier.

For those stars which have a non-negligible amorphous silicate emission in addition to the oxide emission bands, we subtracted a normalized silicate emission profile (of TY Dra) from the respective normalized dust emission spectra (this has been done for θ Aps, EP Aqr, RX Boo and SV Peg: see Fig. 3). For a more detailed discussion of the method here applied to derive the oxide dust emissivity, see Jäger et al. (2002).

Table 1 summarizes some relevant parameters characterizing our sample stars. The mass loss ("ML") rates, given in units of 10^{-7} $M_\odot$/y, were derived from thermal CO line observations by Olofsson et al. (2002).

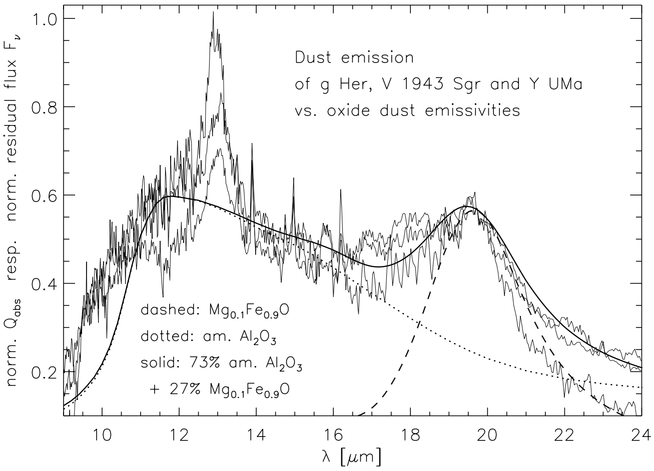

Fig. 2. The normalized (stellar continuum subtracted) dust emission of g Her, V 1943 Sgr and Y UMa compared to the scaled absorption efficienies of $Mg_{0.1}Fe_{0.9}O$, amorphous Al_2O_3 and a mixture of both oxide dust species.

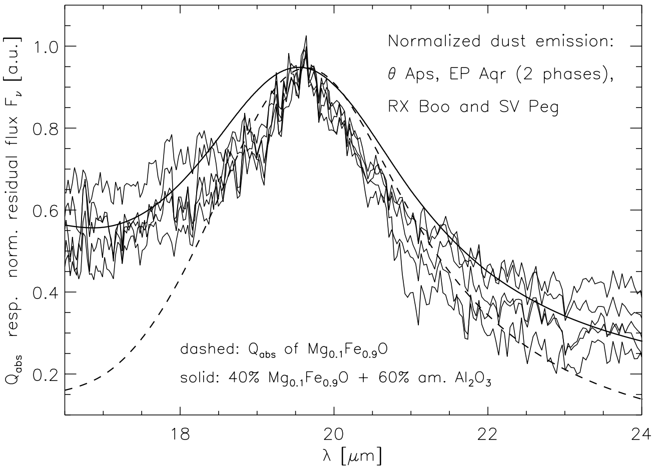

Fig. 3. The 19.5 μm emission feature in the spectra of θ Aps, EP Aqr, RX Boo and SV Peg compared to the scaled absorption efficiency of $Mg_{0.1}Fe_{0.9}O$ particles (dashed) and a 40:60 mixture of them with amorphous Al_2O_3 particles (solid).

3. The quest for the feature carrier

It has been noted by various authors that FeO is a potential carrier of a broad ~20 μm emission feature seen in various types of oxygen-rich dust shells (see e.g. Begemann et al. 1995; Malfait et al. 1999; Demyk et al. 1999; Molster 2000). In this respect, we are not the first to propose that there may be *some* connection between an Fe-rich oxide and an excess emission in the 19–20 μm spectral range. In fact – as pointed out in the previous section – such a relationship had been suspected even before ISO data became available (Bagnulo & Doyle 1997).

The new idea to be put forward here is just the following: Based on the ISO-SWS spectra especially of "hot" semiregular variables and on the optical constants due to Henning et al. (1995), it becomes possible to *find out which solid solution out of the MgO-FeO-system is responsible for the 19.5 μm band* presented above.

Table 2. Diagnostic spectral parameters of small Mg-Fe-oxide particles with different stoichiometries ("x" denoting the fraction of the metal ions being Mg): Positions of the maxima of the predicted features in case of mean dust temperatures of 350 K ("λ_{F350}") and 200 K ("λ_{F200}"); corresponding full width at half maximum values ("w"); positions of the maximum of the absorption coefficient for a weighted continuous distribution of ellipsoids ("$\lambda_{\rm C,CDE}$"). All values are given in units of μm.

x	λ_{F350} / width	λ_{F200} / width	$\lambda_{\rm C,CDE}$ / width
1.0	16.6 / w0.5	16.6 / w0.5	17.1 / w6.2
0.6	17.6 / w2.9	17.8 / w2.9	18.4 / w7.6
0.5	18.4 / w3.2	18.5 / w3.2	19.5 / w7.1
0.3	18.8 / w3.2	18.9 / w3.2	19.9 / w7.0
0.2	19.2 / w3.5	19.3 / w3.5	20.2 / w7.2
0.1	*19.6 / w3.3*	*19.7 / w3.3*	20.7 / w7.3
0	19.9 / w3.6	20.0 / w3.7	21.0 / w7.5

In order to properly treat this problem, two effects influencing the band position and width of these oxides have to be taken into account. The first is the influence of the particle shape, which has already been discussed by Henning et al. (1995). The second important point is the influence of the dust temperature on the absorption (and scattering) efficiencies.

Concerning the shape effects, it is important to stress that Mg-Fe-oxides have cubic crystall symmetry. This makes it very unlikely that strongly prolate or strongly oblate Mg-Fe-oxide particles dominate in a circumstellar shell. Continuous distributions of ellipsoids cannot be ruled out by this argument. However, such shape distributions lead to the prediction of more than 7 μm wide bands, which is definitely not consistent with the observations presented in Sect. 2.

As far as the dust temperature is concerned, assuming a mean dust temperature of 500 K leads to a shift of the predicted SED peak position by 0.1 μm towards the "blue" compared to the case of $T = 350$ K. On the other hand, a mean dust temperature of 200 K leads to a shift towards the "red" by about the same amount. In view of the mentioned instability of Mg-Fe-oxides at high temperatures, only the case of low temperatures ($T \leq 350$ K) is considered here. Table 2 gives an overview of the temperature effects. Note that in Figs. 2 and 3, $Q_{\rm abs}$ and not its product with a Planck function $B_\nu(T)$ (or an integral over several $B_\nu(T)$) has been plotted. This has the advantage of being independent from assumptions on the dust temperature T; however, taking into account the influence of $B_\nu(T)$ will slightly modify the feature position – as indicated in Table 2 – and its shape.

This table confirms the result anticipated in Figs. 2 and 3: $Mg_{0.1}Fe_{0.9}O$ (or eventually a mixture of different Mg-Fe-oxides with $Mg_{0.1}Fe_{0.9}O$ being the most abundant one), can almost ideally account for the observed 19.5 μm emission. It is a puzzling question why mainly $Mg_{0.1}Fe_{0.9}O$ should form in a circumstellar shell (and not either pure FeO or e.g. $Mg_{0.5}Fe_{0.5}O$). In this context, it is interesting that under terrestrial conditions, *pure* FeO does not form anyway, but a compound with the stoichiometry $Fe_{0.84}O$ to $Fe_{0.95}O$ (Holleman & Wiberg 1995). It may be that in Mg-rich environments, the voids in the $Fe_{1-x}O$ lattice tend to be occupied by Mg ions.

To shortly address the question of *alternative carriers* of the band here attributed to $Mg_{0.1}Fe_{0.9}O$, it should be recalled that the following materials can also produce emission bands near 20 μm: crystalline α-Al_2O_3, amorphous SiO_2 particles (Begemann et al. 1997; Posch et al. 1999) and TiC clusters (von Helden et al. 2000). However, the first two dust species would produce very strong additional features, for which no observational evidence exists (α-Al_2O_3: features at 12.7 and 21.0 μm in addition to that at 19.9 μm; SiO_2: features at 8.8 and 12.3 μm in addition to that at 20.5 μm). TiC nanoparticles, on the other hand, radiate efficiently at a wavelength of 20.1 μm, but this is neither in exact agreement with what we observe nor do we expect carbide dust to be abundant in the shells of oxygen-rich stars.

4. Conclusions

We have detected and tentatively identified a broad dust emission feature peaking at 19.5 μm which is especially prominent in AGB stars with comparatively *high* temperatures and *low* mass-loss rates. No dust species yields such a good agreement with the observed astronomical spectra as $Mg_{0.1}Fe_{0.9}O$ does with respect to the band width, shape and position. A mixture of different Mg-Fe-oxides (with $Mg_{0.1}Fe_{0.9}O$ being the most abundant one) may also be compatible with the observational data.

Of course it is a pity that Mg-Fe-oxides do not have more than one strong resonance vibration band in the infrared. In this respect, they behave totally different from spinels and crystalline silicates. The latter substances produce a characteristic pattern of lattice vibration bands, making their identification more reliable. However, this shortcoming is compensated by the above mentioned fact that there is presently no alternative dataset able to reproduce the 19.5 μm feature.

The feature identifications presented in this paper seem to have important consequences for the understanding of the formation and evolution of circumstellar dust. On the basis of the analysed spectra (especially those of g Her, V 1943 Sgr and Y UMa), we postulate the existence of a distinct class of circumstellar dust shells which are dominated by oxides and not by silicates. Their dust spectra can be reproduced by a combination of amorphous Al_2O_3, spinel and $Mg_{0.1}Fe_{0.9}O$. In view of the low optical depths and high photospheric temperatures of these stars, it is reasonable to assume that Al-, Mg-Al- and Mg-Fe-oxides represent the first spectroscopically detectable dust species to condense in O-rich circumstellar shells (even though this is not in perfect accordance with present results of thermodynamical calculations and experimental investigations.) Some of our sample stars (θ Aps, EP Aqr, RX Boo and SV Peg) show non-negligible silicate emission in addition to the emission features characteristic of oxides containing Mg, Al and Fe. Therefore, these objects represent the transition to intermediate mass-loss stars dominated by amorphous silicates.

The thermodynamical aspects of the spectroscopically infered occurence of circumstellar $Mg_{0.1}Fe_{0.9}O$ are not yet understood, since Mg-Fe-oxides become stable at rather low temperatures compared to other oxides and the results of condensation experiments do not deliver any evidence for the formation of mixed Mg-Fe-oxides directly from the gas phase. The possible implications of these discrepancies deserve further investigation.

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