Astron. Astrophys. 341, L67–L70 (1999)

ASTRONOMY AND ASTROPHYSICS

LETTER

*Letter to the Editor*

# Dust in R71: first detection of crystalline silicates in the LMC*

**R.H.M. Voors[1,2], L.B.F.M. Waters[3,4], P.W. Morris[1,3], N.R. Trams[5], A. de Koter[3], and J. Bouwman[3]**

[1] SRON Laboratory for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
[2] Astronomical Institute, University of Utrecht, Princetonplein 5, 3508 TA Utrecht, The Netherlands
[3] Astronomical Institute Anton Pannekoek, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
[4] SRON Laboratory for Space Research, PO Box 800, 9700 AV Groningen, The Netherlands
[5] Integral Science Operations, Astrophysics Division of ESA, ESTEC SCI-SAG, P.O. Box 299, 2200 AG Noordwijk, The Netherlands

Received 12 November 1998 / Accepted 27 November 1998

**Abstract.** We present infrared spectroscopy taken with the Infrared Space Observatory (ISO) of the Luminous Blue Variable (LBV) R71 in the Large Magellanic Cloud (LMC). The spectrum shows clear evidence for the presence of crystalline olivine at 23.5 $\mu$m. This is the first detection of circumstellar crystalline silicates outside our galaxy. In addition, we identify emission at 6.2, 7.7 and possibly 8.6 $\mu$m from C-rich small grains (PAHs). The presence of C-rich grains is not expected in an environment where C/O is less than 1. We fit the dust spectrum using a radiative transfer model and find a dust mass of 0.02 $M_\odot$. R71 was probably a Red Supergiant when it produced the dust shell and had a time-averaged mass loss rate of the order of $7 \times 10^{-4}$ $M_\odot$ $yr^{-1}$ for a gas/dust ratio of 100.

**Key words:** stars: circumstellar matter – stars: evolution – stars: individual: R71 – stars: mass-loss – infrared: stars

## 1. Introduction

The evolution of the most massive stars in galaxies is dominated by extensive mass loss throughout their entire life. This mass loss is important because it influences stellar evolution and affects the interstellar medium in galaxies by means of mass, energy and momentum input. While the physical mechanism responsible for mass loss during core-hydrogen burning (radiation pressure on ions of trace elements of C, N, O and other metals) is reasonably well understood (Castor et al. 1975), the situation is much less clear for the post-main-sequence phase. A small group of hot, massive supergiants, the Luminous Blue Variables (LBVs) can develop instabilities leading to changes in $T_{eff}$ on timescales of years at roughly constant luminosity, and can show sudden bursts of mass loss (Humphreys & Davidson 1994, Nota & Lamers 1997). The physical mechanism for these variations is not clear.

In order to better understand the physics of LBVs, it is useful to reconstruct their mass loss history. This can readily be done since almost all LBVs are associated with ring nebulae, most of them containing a large amount of dust. These dusty ring nebulae are the fossils of previous mass loss phases, and their structure reveals much about the past events that led to their formation (see e.g. Nota et al. 1995; García-Segura et al. 1996). We have started an observational study of the dust emission of LBV ring nebulae, using ground-based imaging to study the nebular morphology and infrared spectroscopy to establish the nature of the grains in these dust shells. The goal is to determine the physical conditions during the dust formation process. In particular we wish to address the question whether these dusty LBV ring nebulae are produced during (violent) outbursts in the hot OB-type evolution phase or during a phase when the star was a cool yellow or red supergiant. The distribution of stars in the upper HR diagram (Humphreys & Davidson 1984) suggests that stars with an initial mass above $\approx$50 $M_\odot$ do not evolve into red supergiants (RSGs). However, there are some LBVs with an initial mass above this limit with massive dust shells. Waters et al. (1997; 1998) have pointed out the similarity in dust properties of the dust shell of one LBV, AG Car, to that of RSGs. These similarities suggest similar physical and chemical conditions in the dust forming layers of RSGs and LBVs.

In this *Letter*, we present new observations of R71, a well-studied LBV in the Large Magellanic Cloud (LMC). We will demonstrate that the dust shell, first studied by Glass (1984) and Wolf & Zickgraf (1986), consists of both amorphous and crystalline silicates. This is the first detection of circumstellar crystalline silicates outside our galaxy. We have organized this paper as follows: in Sect. 2 we discuss the observations and in Sect. 3 we compare the dust properties with those of the galactic RSG NML Cyg. In Sect. 4, we present a dust model fit and Sect. 5 contains a discussion of our results.

## 2. Observations

We have observed R71 using the Infrared Space Observatory (ISO; Kessler et al.1996) as part of our open time programme on LBVs in the Magellanic Clouds. We obtained a full scan

*Send offprint requests to*: L.B.F.M. Waters

* based on observations obtained with ISO, an ESA project with instruments funded by ESA Member states (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA

with the Short Wavelength Spectrometer (SWS; de Graauw et al. 1996), AOT01 speed 3, on April 13, 1996. We also obtained a low-resolution spectrum between 2 and 12 $\mu$m using ISOPHOT-S (Lemke et al. 1996). A first analysis of the SWS data revealed an emission bump near 23 $\mu$m. We have obtained discretionary time to take a deep SWS scan in the 12 to 28 $\mu$m wavelength range (SWS AOT06 scan) and low resolution ISOCAM CVF (Cesarsky et al. 1996) scans in the 5 to 16 $\mu$m wavelength range, using a 3$''$ pixel fov. These observations were carried out on March 14, 1998.

Data reduction of the SWS scans was done using the SWS Interactive Analysis (IA) package version 6.0 following standard data reduction procedures. Similarly, the ISOCAM data were reduced using the CAM Interactive Analysis package (CIA[1]) version 2.0, with the standard processing steps. The spectra were calculated over a 5$\times$5 pixel area centered on the source. The background was calculated over a similar 5$\times$5 pixel area off source, to correct for zodiacal flux contribution. This contribution was negligible for the longer wavelengths, where the radiation from the dust shell dominates. The PHOT-S spectrum was reduced using the PHOT Interactive Analysis system (PIA[2]) version 6.0. The PHOT-S and CAM-CVF spectra are very similar in shape and flux level; we will not show the PHOT-S spectrum here.

The two SWS scans (AOT01 and AOT06), agree well in the 19.5-28 $\mu$m wavelength range (SWS band 3D), but deviate significantly shortwards of 19.5 $\mu$m (SWS band 3A and 3C). The AOT01 scan and the CAM CVF data agree very well in the region of overlap where the S/N of the SWS scan is reasonable (SWS band 3C). Therefore, we used the overall shape of the SWS01 scan to define the location of the continuum longwards of 16 $\mu$m (the longest wavelength CAM data point), and the AOT06 scan in band 3D ($19.5 < \lambda < 28.0$ $\mu$m) where it has superior S/N compared to the AOT01 scan. This procedure introduces some uncertainty in the detailed shape of the steep rise in flux between 16 and 19.5 $\mu$m. The final spectrum is displayed in Fig. 1. The flux levels agree well with the IRAS Point Source Catalogue data.

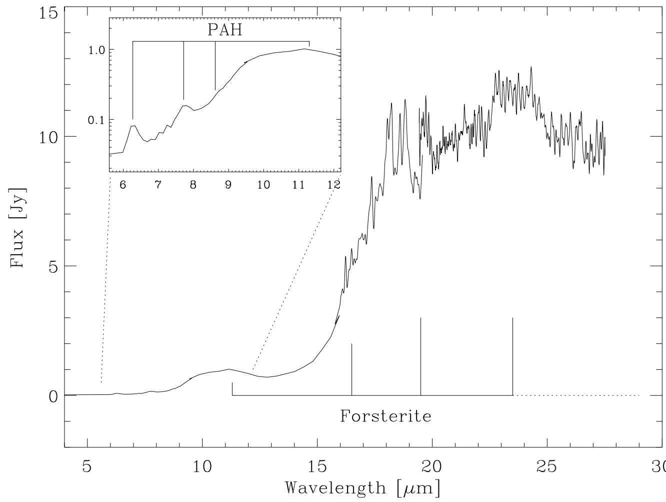


**Fig. 1.** Combined ISOCAM CVF ($6 < \lambda < 16\mu$m), SWS01 ($16 < \lambda < 19.5\mu$m) and SWS06 ($19.5 < \lambda < 28\mu$m) spectrum of R71. The inset shows the 6 to 12 $\mu$m region with the PAH emission bands. We indicate the wavelength of the expected bands of forsterite ($Mg_2SiO_4$), a crystalline olivine.

## 3. Solid state features

Both the low-resolution CAM spectrum and the PHOT-S spectrum reveal the presence of a prominent amorphous silicate feature, which peaks at 10.5 $\mu$m. The presence of the silicate feature indicates that the dust is oxygen-rich, i.e. C/O $< 1$. This silicate feature was previously detected by Roche et al. (1993). The strength of the feature suggests that these silicates are rather warm ($T > 150$ K). The SWS spectrum shows a sharp rise at 16-17 $\mu$m, and is rather flat between 20 and 28 $\mu$m. A clear and surprisingly strong emission feature is detected near 23-24 $\mu$m with a strength of about 2 Jy or 20 per cent over continuum. A 23.5 $\mu$m feature is often found in the spectra of cool, oxygen-rich envelopes and is attributed to crystalline olivine ($Mg_{2x}Fe_{2-2x}SiO_4$; Waters et al. 1996; Jäger et al. 1998). To our knowledge, this is the first detection of circumstellar crystalline olivine outside the galaxy. The 23 $\mu$m complex probably is a blend of two features, one centered around 23 $\mu$m (unidentified; Molster et al. in preparation), and the olivine band near 23.5 $\mu$m. The steep rise between 16 and 19.5 $\mu$m can be understood in terms of the contribution of both the amorphous 18 $\mu$m silicate band as well as the 16.5 and 19.5 $\mu$m crystalline olivine bands.

The observed wavelength of the olivine band can be used to determine the Fe/Mg ratio (Koike et al. 1993; Jäger et al. 1998); the 23.5 $\mu$m feature shifts to longer $\lambda$ with increasing Fe/Mg ratio. Since only one olivine band (viz. at 23-24 $\mu$m) is clearly detected (the narrow peaks between 17 and 20 $\mu$m are probably not real and the SWS spectrum between 30 and 45 $\mu$m is very noisy; there may be a peak near 34 $\mu$m), it is difficult to put firm limits on the Fe/Mg ratio; we estimate an Fe/Mg ratio of less than 20 percent. based on comparison of the 23 $\mu$m complex with sources with well determined Fe/Mg ratios.

In Fig. 2 we compare the 20-28 $\mu$m spectrum of R71 to the continuum subtracted SWS spectrum of the luminous RSG NML Cyg (Justtanont et al. 1996). Note the similarity in shape of the 23 $\mu$m complex. The SWS spectrum of NML Cyg shows the presence of both crystalline olivines and pyroxenes. For NML Cyg, the 33.8 $\mu$m olivine peak suggests an Fe/Mg ratio of 5 per cent or less. Given the similarity in the 23 $\mu$m region between both stars, this value may also apply to R71.

Fig. 1 shows clear evidence for emission bumps at 6.2, 7.7, 11.3 and possibly also at 8.6 $\mu$m. These features can be attributed to C-H and C-C stretching and bending modes in large aromatic

[1] CIA is a joint development by the ESA Astrophysics Division and the ISOCAM Consortium led by the ISOCAM PI, C.Cesarsky, Direction des Sciences de la Materie, C.E.A., France

[2] PIA is a joint development by the ESA Astrophysics Division and the ISOPHOT consortium led by the Max Planck Institute for Astronomy (MPIA), Heidelberg. Contributing ISOPHOT Consortium Institutes are DIAS, RAl, AIP, MPIK and MPIA

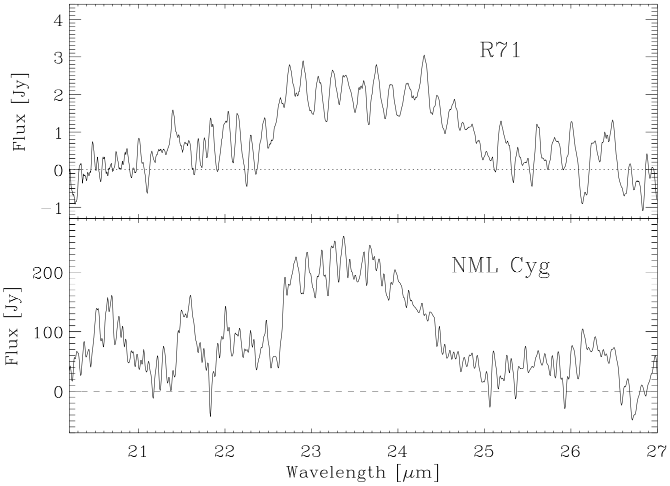


**Fig. 2.** Continuum subtracted SWS spectra of R71 (*top*) and the M supergiant NML Cyg (*bottom*). Note the strong similarity in emission band shape. The band probably consists of two contributions, one at 23 $\mu$m (unidentified) and the forsterite ($Mg_2SiO_4$) band at 23.5 $\mu$m.

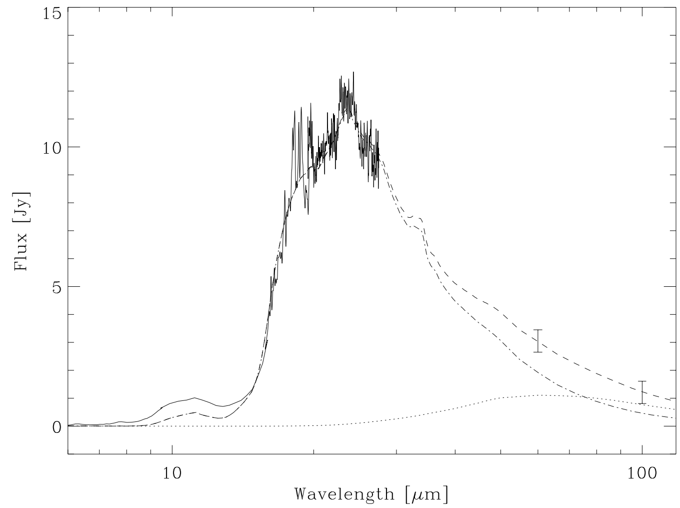


**Fig. 3.** Dust model fit to the ISO spectrum of R71. The full line is the observed spectrum. The dash-dotted line is the dust shell model. The dotted line represents a possible second outer dust shell. The dashed line gives the sum of both components. The discrepancy near 10 $\mu$m suggests the presence of an additional warm dust ($T \simeq 300$ K) component.

hydrocarbon molecules (PAHs). We note that the 11.3 $\mu$m feature can also have a contribution from crystalline olivine. The presence of C-rich dust grains in this O-rich environment is intriguing.

## 4. A dust model for R71

We have used the 1D radiative transfer code MODUST (de Koter et al., in preparation) to model the dust emission in R71. We included the IRAS broad-band data at 60 and 100 $\mu$m as well as near-IR photometry taken from Allen & Glass (1976). We use the stellar parameters for R71 derived by Lennon et al (1994), i.e. $T_{\rm eff}$ = 17000 K, log ($L/L_\odot$) = 5.85 and $R_*$ = 95 $R_\odot$. These parameters put R71 near the Humphreys-Davidson luminosity upper limit. A Kurucz (1991) model atmosphere was used to represent the spectral energy distribution of the star. Given the low present-day mass loss rate ($\simeq 10^{-6}$ $M_\odot$ yr$^{-1}$, Leitherer et al. 1989), free-free emission is not expected to be significant, and the Kurucz model should be representative.

We assumed a dust shell composed of amorphous and crystalline olivine (we used forsterite), and FeO. The optical constants were taken from Jäger et al. (1994), Henning et al. (1995), and Servoin & Piriou (1973). A Mathis, Rumple and Nordsieck (1977) grain size distribution ($n(a) \propto a^{-3.5}$) was adopted with grains between 0.1 and 1 $\mu$m and a shape distribution following a Continuous Distribution of Ellipsoids (CDE) for amorphous olivine. We used an $r^{-2}$ density distribution in the shell. We show our best fit model in Fig. 3. The dust shell has innner and outer radii of $5.5 \times 10^4$ and $8.3 \times 10^4$ $R_*$ respectively, and a total dust mass of 0.02 $M_\odot$. The model fits the observed energy distribution very well. The dust mass is a factor of 4 larger than given by Hutsemékers (1997), probably due to different grain opacities. A model with grain sizes between 0.001 and 1 $\mu$m also fits the observations well, and does not significantly change the dust mass of the shell. For the derivation of the olivine abundance, we used spherical grains and MIE theory to fit the strength of the 23 $\mu$m complex, and we find an abundance of 15 per cent by number. Unfortunately, the 23 $\mu$m band is particularly sensitive to grain shape effects. While the wavelength of the peaks is fitted well in CDE, the grain sizes used by us are not in the Rayleigh limit and the use of CDE gives incorrect band strengths for these grain sizes. We estimate that our olivine abundance may be overestimated by a factor of two by these grain shape effects (Molster et al., priv. comm.).

The expansion velocity of the shell is 20 km s$^{-1}$ (Stahl & Wolf 1986); with the dust shell parameters given above, this corresponds to a time-averaged dust mass loss rate of $7 \times 10^{-6}$ $M_\odot$ yr$^{-1}$ over $\sim$ 3000 yrs. The gas/dust ratio is uncertain. If we adopt 100, we find a total mass loss rate of $7 \times 10^{-4}$ $M_\odot$ yr$^{-1}$. This value is similar to that found for AG Car (Waters et al. 1997). The outer radius of the dust shell is not well constrained by our model. However, this does not affect our mass loss estimate, but only the total dust mass and duration of the mass loss phase.

Our model fails to reproduce the 60 and 100 $\mu$m IRAS fluxes. This can have several causes: (i) solid state emission bands at 60 and 100 $\mu$m (Barlow 1998), (ii) incorrect dust emissivities at the longer wavelengths, (iii) a density gradient significantly flatter than $r^{-2}$, or (iv) an additional, cooler dust shell. If the later explanation is the correct one, a second dust shell between $1.2 \times 10^6$ and $1.35 \times 10^6$ $R_*$ with a dust mass of 0.3 $M_\odot$ is required. Its contribution is shown in Fig. 3.

The model also fails to reproduce the fluxes between 5 and 15 $\mu$m, but it does give the correct strength of the 10 $\mu$m amorphous silicate feature. Clearly, a population of warm grains (T$\simeq$ 300 K) must be present. These grains may not be in thermal equilibrium, or they are much closer to the star than the adopted innner boundary of our dust model.

The presence of PAH emission points to a population of very small grains, not in thermal equilibrium. The dust mass associated with the warm component is small, of the order of $10^{-5}$ to $10^{-6}$ $M_\odot$.

## 5. Discussion

The composition of the dust shell of R71 is reminiscent of those of galactic RSG with high mass loss rates (Fig. 2): a dominant contribution of Fe-rich amorphous silicates and an abundance of the order of 10 per cent of Mg-rich, Fe-poor crystalline olivines. The dust around NML Cyg also contains crystalline pyroxenes ($Mg_xFe_{1-x}SiO_3$). The similarity between the 23 $\mu$m features in R71 and NML Cyg suggests that R71, also contains pyroxenes. This points to conditions in the dust forming layers of R71 that must have been very similar to those prevalent in other stars with crystalline silicates: high densities and low gas temperatures (Waters et al. 1996). Indeed, crystalline silicates are observed in stars with ongoing or recent very high mass loss, including RSGs. R71 also follows this pattern, as does the galactic LBV AG Car (Waters et al. 1997). The expansion velocity of the R71 shell (20 km $s^{-1}$) is typical for those in RSGs in the galaxy and in the LMC (e.g. van Loon et al. 1998). This suggests that R71 was a RSG when it produced the dust shell. It is likely that the dust shell was optically thick during this brief RSG period and that the object was a bright far-IR source.

It is interesting to consider the consequences of a brief RSG phase of R71 for our understanding of massive star evolution. Observationally, there appear to be no very luminous RSG with $\log(L/L_\odot) > 5.8$ (Humphreys & Davidson 1984). There is some discussion in the literature about the luminosity of R71. Wolf et al. (1981) derive $\log(L/L_\odot) = 5.3$ but Lennon et al. (1994) argue that R71 has an anomalous extinction law and find $\log(L/L_\odot) = 5.85$. In either case, R71 is either below or just at the Humphreys-Davidson limit if it evolves to the red part of the HR diagram. Therefore, a brief RSG phase of R71 does not violate the observed lack of very luminous RSG in galaxies.

The presence of PAHs in R71 is surprising, since these C-bearing large molecules or small grains are not expected to form in an oxygen-rich environment. PAH emission was also tentatively found in ISOCAM images of the LBV AG Car (Trams et al. 1996) as well as in HD 168625 (Skinner 1997). It is clear that there is a population of very small grains. Lennon et al. (1994) noted an unusual shape of the UV extinction law towards R71: a steep far-UV rise but no 2175 Å bump. Perhaps this peculiar extinction law is due to the warm, small circumstellar grains we have detected in our ISO spectra. If these are located at the inner radius of the dust shell, the column density is too small to cause the the large UV extinction noted by Lennon et al. (1994). Therefore an interstellar origin for the anomalous far-UV extinction cannot be excluded.

*Acknowledgements.* LBFMW, AdK and JB acknowledge financial support from an NWO *Pionier* grant. We are much indebted to H. Lamers for critically reading the manuscript.

## References

Allen, D.A., Glass, I.S., 1976, ApJ 210, 666
Barlow, M.J., 1998, Astrophys. Sp. Sc. 255, 315
Castor, J.I., Abbot, D.C. & Klein, R.I., 1975, ApJ 195, 157
Cesarsky, C.J. et al., 1996, A&A 315, L32
De Graauw, Th. et al., 1996, A&A 315, L49
García-Segura G., Mac Low M., Langer N., 1996, A&A 305, 229
Glass, I.S.,1984, MNRAS 209, 759
Henning, Th., Begemann, B., Mutschke, H., et al., 1995, A&AS 112, 143
Humphreys R.M., Davidson K., 1984, Science 223, 243
Humphreys R.M., Davidson K., 1994, PASP 106, 1025
Hutsemékers D., 1997, ASP Conference series vol. 120, eds. A. Nota & H.J.G.L.M. Lamers, p. 316
Jäger, C., Mutschke, H., Begemann, B., et al., 1994, A&A 292, 641
Jäger, C., Molster, C., Dorschner, et al., 1998, A&A 339, 904
Justtanont, K., et al., 1996, A&A 315, L217
Kessler, M.F., et al., 1996, A&A 315, L27
Koike, C., Shibai, H., Tuchiyama, A., 1993, MNRAS 264, 654
Kurucz, R., 1991, in *Stellar Atmospheres–Beyond Classical Models*, ed. Crivellari, L., Hubeny, I., Hummer, D.G., NATA ASI Series, Series C, Vol. 341, 441
Leitherer, C., Abbott, D.C., Schmutz, W., 1989, in *Physics of Luminous Blue Variables, eds. Davidson K., Moffat A. and Lamers H.*, p. 109
Lemke, D., et al., 1996, A&A 315, L64
Lennon, D.J., Wobig, D., Kudritzki, R.-P., et al., 1994, Sp.Sc.Rev. 66, 207
Mathis, J.S., Rumpl, W., Nordsieck, K.H., 1977, ApJ 217, 425
Nota, A., Lamers, H.J.G.L.M., 1997 *Luminous Blue Variables: massive stars in transition* ASP Conf Ser. 120
Nota, A., Livio, M., Clampin M., et al., 1995, ApJ 448, 788
Roche, P.,F., Aitken, D.K., Smith, C.H., 1993, MNRAS 262, 301
Servoin, J.L., Piriou, B., 1973, Phys. Stat. Sol. (b) 55, 677
Skinner, C.J., 1997, ASP Conference series vol. 120, eds. A. Nota & H.J.G.L.M. Lamers, p. 322
Stahl, O., Wolf, B., 1986, A&A 158, 371
Trams, N.R., Waters, L.B.F.M., Voors, R.H.M., 1996, A&A 315, L213
Van Loon, J.Th., Te Lintel Hekkert, P., Bujarrabal, V., et al., 1998, A&A 337, 141
Waters, L.B.F.M., et al., 1996, A&A 315, L361
Waters, L.B.F.M., Morris, P.W., Voors, R.H.M., Lamers, H.J.G.L.M., 1997, ASP Conference series vol. 120, eds. A. Nota & H.J.G.L.M. Lamers, p. 326
Waters, L.B.F.M., Morris, P.W., Voors, R.H.M., et al., 1998, Astrophys. Sp. Sc. 255, 179
Wolf, B., Appenzeller, I., Stahl, O., 1981, A&A 103, 94
Wolf, B., Zickgraf, F.-J., 1986, A&A 164, 435