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THE NEAR-INFRARED SPECTRUM OF THE HERBIG Ae–Be STARS

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ABSTRACT

Infrared photometry in the J, H, K, L, and M bands has been carried out for a sample of Ae–Be stars associated with nebulosity. The observational data are compared with theoretical models to account for the infrared excess. A general agreement with the observations is found by adopting a model in which the main source of IR emission is the bremsstrahlung from H_2^-. Some exceptions, represented by LkHα 198, R Mon, and LkHα 233, are discussed. Two of the stars, BD +41°3731 and LkHα 215, do not show appreciable IR excess.

Subject headings: radiation mechanisms — stars: circumstellar shells — stars: emission-line — stars: pre–main-sequence

I. INTRODUCTION

The first attempt to identify the signposts of early-type star formation was made by Herbig (1960). He compiled a list of 26 Ae and Be stars, candidates for newborn stars, on the basis of photographic and spectroscopic appearance.

Since this work many investigators have contributed to this subject through spectroscopic (Strom *et al.* 1972*b*; Garrison and Anderson 1977), polarimetric (Breger 1974; Vrba 1975; Vrba, Schmidt, and Hintzen 1979; Garrison and Anderson 1978), UV (Sitko, Savage, and Meade 1981), IR (Gillett and Stein 1971; Strom *et al.* 1972*a*; Cohen 1973, 1980; Allen 1973), and radio (Loren 1977, 1981) studies, providing evidence of the youth of these objects. Recently Garrison (1978) observed quite a number of these stars, pointing out that their spectrum up to 8500 Å can be accounted for by bremsstrahlung in the surrounding H II region.

However, the attempts to extend the validity of this mechanism to explain the additional IR flux observed at longer wavelengths have been unsuccessful because of the small extension of the ionized region and, consequently, the small emission measure involved. Two approaches could, in principle, be proposed to overcome this difficulty. The traditional argument invoked in such cases is based on the emission from circumstellar dust shells, but in 1972 Dyck and Milkey pointed out the possibility that free-free and free-bound processes occur in an external H I region with nonnegligible effects on the IR spectrum.

In this paper we present near-infrared photometric data for a sample of these stars together with a brief discussion on the emission mechanism.

II. OBSERVATIONS

J, H, K, L, M photometry has been carried out at the 1.82 m telescope at Cima Ekar (Asiago) and at the 1.5 m IR telescope at Gornergrat (Switzerland). The photometer used was equipped with standard IR filters and InSb detector cooled at 77 K (for the details see Baldetti *et al.* 1980). The observations were scattered over a period of 1 yr between 1980 September and 1981 November. The calibration procedure used is based on the comparison with the absolute calibration of a set of standard stars given by Strecker, Erickson, and Witteborn (1979). Atmospheric extinction has been considered even if the corrections applied are typically less than the uncertainty introduced by the atmospheric fluctuations (~ 0.1 mag).

In Table 1 the observed magnitudes are presented, and in Figure 1 the same results are shown in graphic form after correction for interstellar reddening. The applied corrections are mainly based on the $E(B-V)$ given by Strom *et al.* (1972*b*) and the interstellar extinction curve derived by Johnson (1965) for the Perseus region. Actually, because of the uncertainty in $E(B-V)$ for R Mon, T Ori, MWC 1080, and LkHα 198, no reddening correction is possible for these stars. However, for R Mon and MWC 1080 a rough estimate has been made through the spectral type and the $(B-V)$ available in the literature. It should be noted that, in principle, the standard Perseus curve cannot be applied to all directions because of the appreciable regional variations of the extinction. In fact, if two extreme reddening curves are used for our case, the difference introduced in the graphs can amount to 0.7 mag when $\lambda = 5\ \mu$m and $E(B-V) = 0.5$. The Perseus curve should, however, correspond to a minimum reddening, and the correction applied here is actually a lower limit.

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TABLE 1

Observed Magnitudes

Star	*J*	*H*	*K*	*L*	*M*
LkHα 198........	9.9	7.9	6.3	4.1	3.7
BD +61°154	8.5	6.9	5.7	4.3	4.0
AB Aur...........	6.1	5.1	4.4	3.3	2.9
HK Ori...........	9.4	8.4	7.4	5.7	4.9
T Ori	8.4	7.4	6.5	5.3	4.8
V380 Ori	8.0	7.0	5.9	4.2	3.7
RR Tau...........	9.7	8.3	7.1	5.8	5.5
LkHα 215........	5.9	5.6	5.5	5.4	5.4
R Mon	9.5	7.8	5.9	3.1	...
Z CMa	5.7	4.7	3.8	1.6	1.0
BD +40°4124 ...	8.0	6.9	5.7	4.2	3.8
BD +41°3731 ...	9.9	9.8	9.9	9.6	...
HD 200775.......	6.1	5.5	4.7	3.4	2.9
BD +65°1637 ...	9.0	8.7	8.6	8.0	7.5
LkHα 234........	9.3	8.1	6.8	5.3	4.7
BD +46°3471 ...	8.6	7.7	6.7	5.1	...
LkHα 233........	11.2	10.0	8.3	6.1	5.5
MWC 1080.......	7.4	6.0	4.7	2.9	2.4

Note.—Error ~0.1 mag.

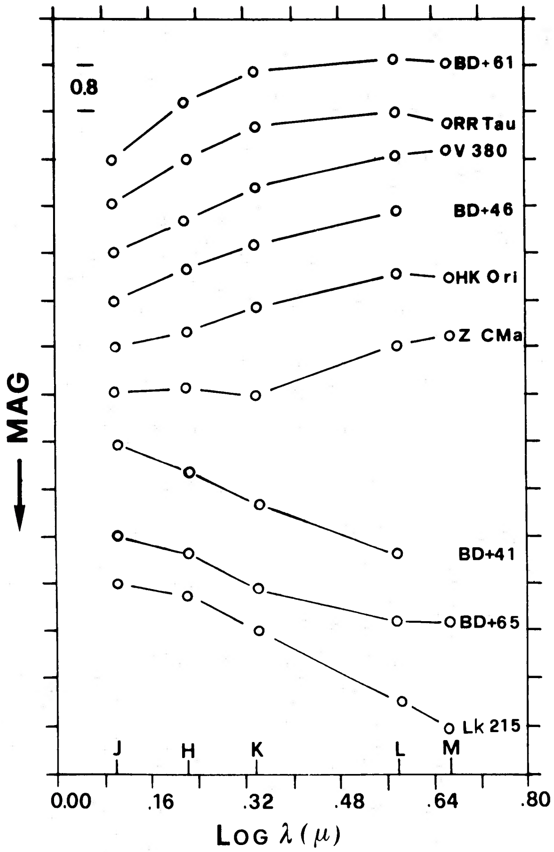

Fig. 1*a*

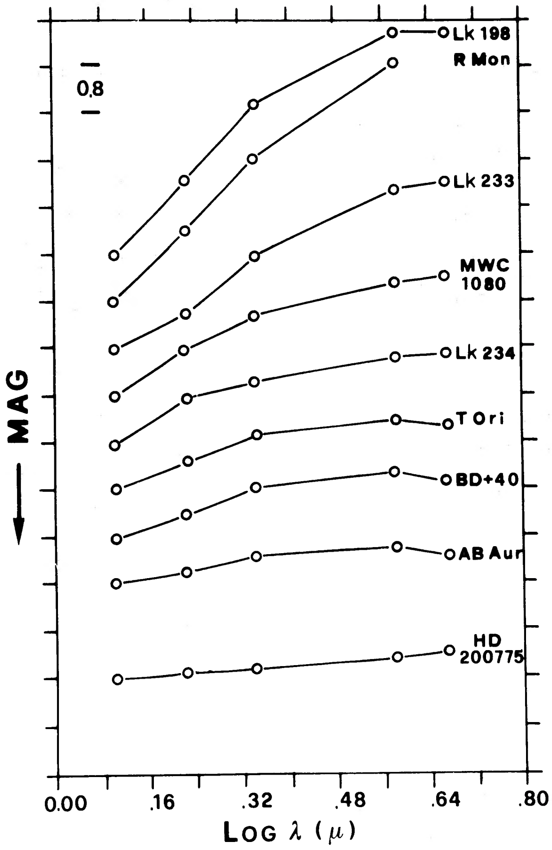

Fig. 1*b*

Fig. 1.—(*a*) Dereddened spectra for a sample of Herbig Ae–Be stars. The ordinate scale is in magnitudes defined as $2.5 \log F_\nu / F_{\nu(0.55\ \mu\mathrm{m})}$. (*b*) As in (*a*), but the reddening correction is uncertain for R Mon and MWC 1080 and is not applied for LkHα 198 and T Ori (see text).

III. THE MODEL

a) The Bremsstrahlung Hypothesis

Some years ago Dyck and Milkey (1972) contributed to the debate about the origin of the IR excess in early-type stars with the original hypothesis that this excess could be due to bremsstrahlung processes occurring in an extended neutral region around these stars. In this hypothesis the emission is dominated by processes involving atomic or molecular hydrogen and free electrons. The latter should be provided by metals with ionization potential below 13.6 eV under the influence of the stellar radiation with $\lambda > 912$ Å. This simple picture has been successfully checked by Dyck and Milkey against its ability to reproduce the observed continuum spectrum under realistic physical conditions. Here we shall only summarize some specific results for the observed objects.

In the following we make use of the magnitude difference ΔM_ν defined as

$$\Delta M_\nu = -2.5 \log \frac{L_\nu^*}{L_\nu^* + L_\nu^{\mathrm{H\,II}} + L_\nu^{\mathrm{H\,I}}}, \qquad (1)$$

where L_ν^*, $L_\nu^{\mathrm{H\,II}}$, and $L_\nu^{\mathrm{H\,I}}$ are the luminosities per unit frequency interval of the star, the H II, and the H I regions, respectively.

Considering the optically thin case, ΔM_ν is a measure of the IR excess due to the simple additivity of all contributions. In fact, this approximation holds for the small H II region around Ae–Be stars, as discussed by Garrison (1978). Furthermore, it is easily shown that an optically thick H I region would require an exceedingly high column density because of the extremely low value of the free-free absorption coefficient. On these grounds we will adopt the optically thin approximation so that the IR emission can be simply computed by integrating the appropriate emission coefficient over the entire volume involved.

In this case we can write for the different contributions

$$L_\nu^* = 4\pi R^{*2} \pi F_\nu^*, \qquad L_\nu^{\mathrm{H\,II}} = \int_{\mathrm{H\,II}} 4\pi j_\nu^{\mathrm{H\,II}}\, dV,$$

$$L_\nu^{\mathrm{H\,I}} = \int_{\mathrm{H\,I}} 4\pi j_\nu^{\mathrm{H\,I}}\, dV, \qquad (2)$$

where πF^* and R^* are, respectively, the stellar surface flux and radius, and

$$j_\nu^{\mathrm{H\,II}} = N_e N_i R \bar{v} \frac{h}{kT} e^{-h\nu/kT} [\bar{g}(T,\nu) + f(T,\nu)], \qquad (3)$$

where R is a constant, $\bar{v}$ is the average electron speed, $\bar{g}$ is the average Gaunt factor, and f is a function accounting for free-bound transitions, is the emission coefficient given by Brussaard and van de Hulst (1962). Finally, $j_\nu^{\mathrm{H\,I}}$ is the emission coefficient of the H^- free-free that can be obtained from the series expansion of the absorption coefficient given by Gingerich (1961).

It should be noted that in the H I region the electron-ion process (eq. [3]), although more efficient, proceeds at a slower rate because of the relative abundance of the metals, so that it can be neglected.

Now by combining the preceding equations and rearranging we obtain

$$\Delta M_\nu = -2.5 \log \frac{\pi F_\nu^*}{\pi F_\nu^* + \varepsilon^{\mathrm{H\,II}} X_\nu^{\mathrm{H\,II}} + \varepsilon^{\mathrm{H\,I}} X_\nu^{\mathrm{H\,I}}}, \qquad (4)$$

where

$$\varepsilon = \frac{\int N_e N_{\mathrm{H}}\, dV}{R^{*2}}$$

is the volume emission measure, and X_ν is a function depending on the process involved in the appropriate region.

Equation (4) can now be solved under the assumption that the stars radiate according to their spectral type. This point has been discussed by Garrison (1978) in connection with the derivation of the volume emission measure of the H II region $\varepsilon^{\mathrm{H\,II}}$ for a number of Ae–Be stars. His results are based on spectral observations in the optical region, where the ionized gas is expected to be the dominating source of the excess.

All this allows us to obtain the continuum spectrum for a given star taking $\varepsilon^{\mathrm{H\,I}}$ as a free parameter. The result of this procedure is shown in Figure 2, where the model is applied to V380 Ori.

b) The Dust Hypothesis

Dust is known to be often associated with the circumstellar environments, so that the possibility of IR emission by dust cannot be ruled out *a priori*. Here this case is analyzed in a crude way because we are concerned with estimates more than with a detailed description of models.

In a spherical geometry and in the optically thin case the total emission of the circumstellar dust can be expressed as

$$L_\nu^D = \int_{r_0}^{\infty} 16\pi^2 r^2 a^2 N(r) \phi(\nu, T)\, dr, \qquad (5)$$

where N is the grain number density, ϕ is the IR flux at frequency ν emitted by the grain at temperature T, a is the mean grain radius, and the lower integration limit r_0 is set by the condition that grains cannot survive above their sublimation temperature.

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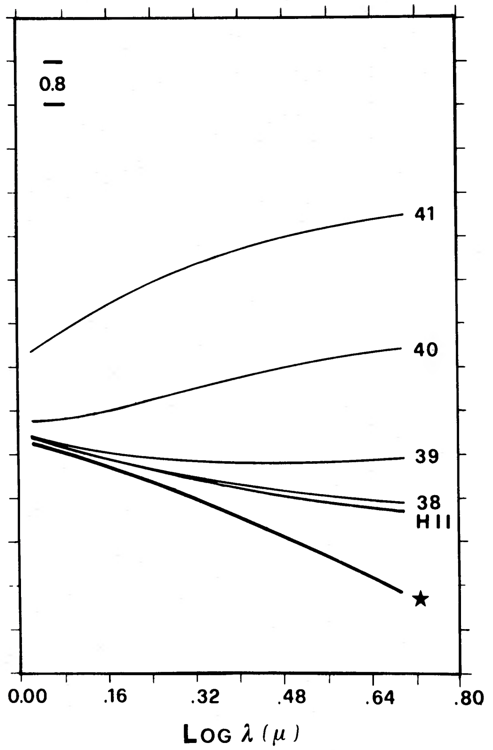

FIG. 2

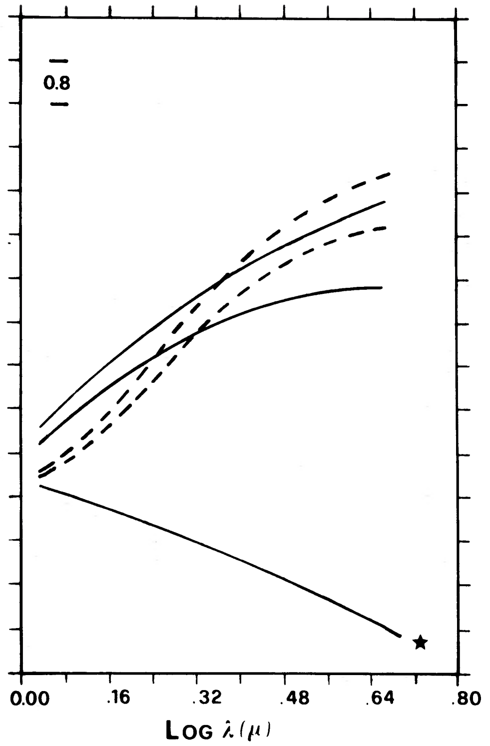

FIG. 3

FIG. 2.—Computed spectrum for V380 Ori on the assumption that the excess is due to bremsstrahlung in an H II region. The lowest curve is the stellar spectrum. The other curves are labeled with the values of $\log \varepsilon^{\mathrm{H\ I}}$ except for the curve labeled H II, which represents the contribution of the H II region only.

FIG. 3.—Computed spectra for an A0 star on the assumption that the IR excess is due to dust. The lowest curve is the stellar spectrum. The adopted values of the parameters are grain radius, 5×10^{-6} cm; initial density, 10^{-2} cm^{-3}; absorption efficiency, 0.5; sublimation temperature, 1800 K (*solid curve*), 1200 K (*dashed curve*); density profile, $\propto r^{-1}$ (*upper curve*), $\propto r^{-2}$ (*lower curve*).

Assuming that the grains radiate as a blackbody and that a density law $N = N_0(r_0/r)^\alpha$ holds, with N_0 the density at the inner boundary of the shell, we obtain, following the procedure outlined in § III*a*,

$$\Delta M_\nu = -2.5 \log \frac{\pi F_\nu^*}{\pi F_\nu^* + C\int_{r_0}^{\infty} \pi B(\nu, T)\, r^{(2-\alpha)}\, dr}, \qquad (6)$$

where $C = (4\pi a^2 N_0 r_0^\alpha)/R^{*2}$.

Equation (6) allows us to compute the expected spectrum with the additional condition that the dust temperature is given by detailed balancing of the absorbed and emitted energy at the appropriate distance.

A grid of models has been computed for different sublimation temperatures, grain radii, densities, and density profiles, taking the dust absorption efficiency equal to 0.5.

The general trend of the spectrum after addition of dust emission is shown in Figure 3, where we show the computed spectra for typical values of the model parameters.

These simple calculations suffer from the assumption of a constant dust emissivity that we adopt in this spectral range because of the uncertainties on the dust composition in such circumstellar envelopes (Cohen 1980). However, Harvey, Thronson, and Gatley (1979), taking into account the effect of a dust emissivity $\varepsilon \propto \nu$, obtain theoretical energy distributions in a number of cases. In their calculations it is noteworthy that a close matching of the observations cannot be obtained for stars included in Herbig's (1960) list, unless a special geometry is invoked accounting for a bump at 5 μm or, alternatively, for a depression at $\lambda > 5$ μm. Self-consistent radiative transfer models have been applied to Z CMa and R Mon by Apruzese (1975) showing that the grains' emissivity decreases with wavelength less than expected for iron-silicate particles. Finally, we note that, if silicates are assumed to be the most likely dust constituents in these objects, their emissivities are slowly varying in our spectral range (Aannestad 1975). Yet, our calculations must be regarded as a simplified approach to the problem, and they cannot rule out the possibility that more specific dust envelope models can account for the IR excess.

IV. DISCUSSION

In this section we shall briefly discuss the applicability of the models to describe the IR spectrum of Ae–Be stars and their limits.

It is worth noting that the observed spectral slope (Fig. 1) is such that the magnitude difference between the points at J and M is less than 1.5 mag for the majority of the stars. This leads one to favor the bremsstrahlung mechanism for its ability to reproduce such small differences together with the observed spectral shape (Fig. 2). From Figure 3 it is in fact apparent that if the dust emission is the dominant process, sensibly larger differences should be observed. Nevertheless, some difficulties concerning the abundance of the molecular hydrogen in the H I region have been raised by Milkey and Dyck (1973) in connection with the problem of the unobserved free-bound emission by H^-. The same authors, however, conclude that the probable source of the observed emission is H_2^-, although uncertainties remain in estimating the abundance.

Because of the importance of this point a brief discussion is in order. If we assume that the abundance equilibrium of the H_2 is essentially determined by the gas phase processes

$$\text{i)}\quad H+H^- \rightleftarrows H_2+e,$$

$$\text{ii)}\quad H+e \rightleftarrows H^- + h\nu,$$

we can express the kinetics of these reactions with a set of detailed balance equations. This set, together with the particle conservation equation, can be solved for $N(H_2)/N(H)$ provided the rate coefficients for the involved reactions are known. Particular attention must be devoted to the rate coefficient of the inverse (i) reaction because of its strong dependence on the relative population of the H_2 excited levels (Wadehra and Bardsley 1978). In the following we adopt the values derived by averaging the cross section over a Maxwellian energy distribution for the electrons and by summing over the vibrational levels of the H_2 populated in thermodynamic equilibrium. With the obtained values and adopting the rates given by de Jong (1972) for the other reactions involved, we derive the relative abundances given in Table 2. The sensible dependence of the H_2 abundance on the temperature as well as on the distance from the central star requires that an accurate model of the circumstellar envelope be adopted before attempting to make any conclusion. We only note that in the simple model adopted by Dyck and Milkey (1972) an appreciable fraction of the emitting volume is found between 50 and 10^3 stellar radii at temperatures of 2500 K or below, thus allowing for the presence of sensible molecular hydrogen amounts. On these grounds we can try to derive $\varepsilon^{\mathrm{H\,I}}$, for those stars with known $\varepsilon^{\mathrm{H\,II}}$, by using the visual magnitudes available in the literature to normalize our spectra to 0.55 μm, where the spectrum is essentially due to the stellar photosphere.

TABLE 2

MOLECULAR HYDROGEN RELATIVE ABUNDANCE, $N(H_2)/N(H)$

DISTANCE	LOG DENSITY (cm^{-3}) 12	13
	$T = 2000$ K	
$10\ R^*$	0.5	1.9
$50\ R^*$	3.3	10.5
$100\ R^*$	6.3	20.5
	$T = 2300$ K	
$10\ R^*$	0.06	0.04
$50\ R^*$	0.7	2.8
$100\ R^*$	1.6	5.5
	$T = 2500$ K	
$10\ R^*$	0.02	0.1
$50\ R^*$	0.3	1.3
$100\ R^*$	0.7	2.8
	$T = 3000$ K	
$10\ R^*$	0.001	0.01
$50\ R^*$	0.03	0.2
$100\ R^*$	0.1	0.5

The results obtained for these stars, although uncertain because of the variability of the objects, cluster around the value of $\varepsilon^{\mathrm{H\,I}} R^{*2} \sim 10^{62}-10^{63}$. It is interesting to note that this value is in order-of-magnitude agreement with the theoretical value expected for a typical Ae–Be star obtained after a detailed analysis of the metals' ionization in the H I region (Dyck and Milkey 1972). If the H_2^- emission is taken into account, a multiplicative factor of 3 should be applied to obtain the actual volume emission coefficient. This means that the total mass of the emitting shell can be roughly estimated if a constant density and a constant $N(H_2)/N(H)$ ratio are assumed. With values, respectively, of $10^{12}-10^{13}$ cm^{-3} and 1, one can obtain $M_{\mathrm{shell}} \sim 10^{-2}$ to 10^{-3} $M_\odot$, suggesting that this emission is confined to a small fraction of the mass expected to be the remnant of the star formation process. However, this general picture has some remarkable exceptions that we can divide into two groups: stars such as LkHα 198, LkHα 233, and R Mon with a "dusty" IR excess, and stars such as LkHα 215 and BD +41°3731 without appreciable excess. In fact, the first group of stars can be matched by a dust model, and the second group is well matched by blackbodies at the temperatures of the corresponding spectral types. Finally, midway we find MWC 1080, which could be represented by a dust model as well as by the bremsstrahlung model.

In the light of these results the Herbig Ae–Be stars appear as a nonhomogeneous set as far as the interaction with the circumstellar environment is concerned. The consistency of the overall picture may be checked by comparison with already published results. In fact, the IR spectroscopy at 10 μm (Cohen 1980) reveals that among the young stars the higher mass objects present featureless spectra showing no evidence for silicate emission. Furthermore, this result has been confirmed by Sitko, Savage, and Meade (1981), who compiled a summary of the properties of 12 dust shell stars in which it is noteworthy that the association with nebulosity is often correlated with a smooth IR spectrum. The only star for which the presence of silicates is without doubt is AB Aur.

In addition, ultraviolet spectra of some of these objects are presented by the same authors, showing the presence of strong absorption lines of singly ionized metals that could be produced in an H I region.

Of course the accuracy of any conclusion is limited by the approximations used in our approach, the most important dealing with the optical thickness and the geometry. As an example we only mention that the polarization observed in such stars makes the spherical geometry improbable. However, this first approximation analysis together with the available data shows a good agreement with the bremsstrahlung hypothesis although the presence of objects like LkHα 198, R Mon, and LkHα 215 point out that this conclusion is not strictly general. A definitive answer about the origin of the IR excess in Herbig's Ae–Be stars cannot be given here because of the aforementioned uncertainties. A better insight into this problem could probably be gained by coordinated IR and optical observations of the variability of these objects.

We are deeply grateful to Professor L. Rosino for the generous allocation of observing time at the Copernico telescope at Cima Ekar. We are also indebted to Professors C. Barbieri and C. B. Cosmovici for the continuous interest and advice in setting up the IR facilities at the Asiago Observatory, and to the staff of the Arcetri Observatory that operates the IR telescope at Gornergrat.

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