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METAL-LINE BLANKETING AND THE PECULIAR Hβ LINE PROFILE IN THE DAO STAR FEIGE 55

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ABSTRACT

A detailed analysis of the optical spectrum of the DAO white dwarf Feige 55 is presented. We show that the atmospheric parameters obtained from fits to the Hβ line and to higher Balmer lines, respectively, are discrepant. This problem is akin to that reported in previous analyses of hot DAO central stars of planetary nebulae. Model atmosphere calculations are used to demonstrate that the discrepancy is likely to be due to the presence of small quantities of heavy elements in the atmosphere of Feige 55. We then show that line blanketing by these elements indeed produces enough cooling of the upper layers to change significantly the predicted line profiles. New models incorporating this opacity source provide excellent agreement with the observed profiles. We discuss several implications of our result on the current analysis of X-ray and EUV fluxes of hot DA and DAO stars.

Subject headings: line: profiles — stars: atmospheres — stars: white dwarfs

1. THE PROBLEM WITH THE BALMER LINES OF DAO STARS

In recent years, considerable progress has been made in our ability to model the line profiles of hydrogen-line (DA) white dwarfs. The spectroscopic technique of fitting observed line profiles to the predictions of model atmosphere calculations has been applied successfully to the analysis of white dwarfs in a wide range of effective temperatures (see, e.g., Bergeron et al. 1990; Daou et al. 1990; Bergeron, Saffer, & Liebert 1992). The quality of the fits achieved in these analyses seemed to indicate that our understanding of line formation in the atmospheres of DA stars was quite complete.

More recently, however, spectroscopic analyses of several central stars of planetary nebulae (PNs) of spectral type DAO have revealed strong discrepancies between the atmospheric parameters derived from individual hydrogen lines (Napiwotzki 1992; Napiwotzki & Schönberner 1992, hereafter NS). This situation is in contrast with the results obtained in cooler DA stars ($T_{\rm eff} \lesssim 40{,}000$ K) where the atmospheric parameters obtained from individual Balmer lines were shown to be internally consistent (Bergeron 1992). The best examples of stars in which this problem has been reported are LS V+46 21 (the central star of the planetary nebula S216) and NGC 7293. In both cases, the Hβ line can be marginally fitted assuming an effective temperature around 50,000 K, while the Hδ line requires a much higher temperature of $T_{\rm eff} \sim 100{,}000$ K. Stellar winds, magnetic fields, uncertainties in the treatment of line broadening, and the presence of metal opacities were invoked by NS to account for the discrepancy. The first three effects were not believed to be significant, while the importance of metals, a perhaps more promising avenue of investigation, was not evaluated.

In an independent investigation, we recently reported on observations of the cooler DAO star Feige 55 (PG 1202+608, GD 314, LB 2197), previously classified as a B subdwarf by Greenstein & Sargent (1974). The optical spectrum of that object is displayed in Lamontagne et al. (1992), where it is also compared with that of PG 1210+533, another DAO star with slightly broader lines. Our best fits to both stars using a grid of LTE model atmospheres calculated under the assumption of homogeneous H/He composition are displayed in Figure 1. Details of our model calculation and line-fitting technique can be found in Bergeron et al. (1992) and references therein. Although the higher members of the Balmer series and the He II λ4686 line are fairly well reproduced in both objects, the line core of Hβ is predicted much too shallow for Feige 55; the agreement is significantly better for PG 1210+533. The atmospheric parameters required to fit the Hβ line profile of Feige 55 are $T_{\rm eff} = 46{,}000$ K and $\log g = 6.6$ (assuming the same value of the helium abundance as in Fig. 1). The lower temperature derived from Hβ alone, as compared with that obtained from other Balmer lines, points to problems similar to those reported by NS for hotter DAO stars. Interestingly, additional calculations with stratified model atmospheres (not displayed here) do not improve on these fits. On the contrary, the He II λ4686 line is then predicted too broad and shallow, as noted also by NS for the star LS V+46 21.

An important clue to the resolution of this problem comes from *IUE* observations of both Feige 55 and PG 1210+533. While *no* photospheric metallic transitions have been reported in the high-dispersion UV spectrum of PG 1210+533 (Holberg et al. 1987, 1988), that of Feige 55, on the other hand, reveals strong absorption features of N V, Si IV, C IV, and more importantly of Fe V and Fe VI. Lamontagne et al. (1992) contrast regions of *IUE* images of Feige 55 with those of G191-B2B, a hot DA star where similar metallic features have been previously detected (see Vennes et al. 1992 and references therein). A simple comparison of the strength of the absorption features reveals that the iron abundance is much higher in Feige 55 than in G191-B2B and in Feige 24, analyzed by Vennes et al. (1992). A detailed analysis of the metal abundance of Feige 55 is underway, the results of which will be reported separately.

There is therefore strong circumstantial evidence that the difference in the quality of the fits, especially at Hβ, between Feige 55 and PG 1210+533 (Fig. 1) could indeed be attributed to the effect of metallic ions that are present in the former star and not in the latter. This explanation, which is also consistent with the *independent* suggestion that the atmospheric structure

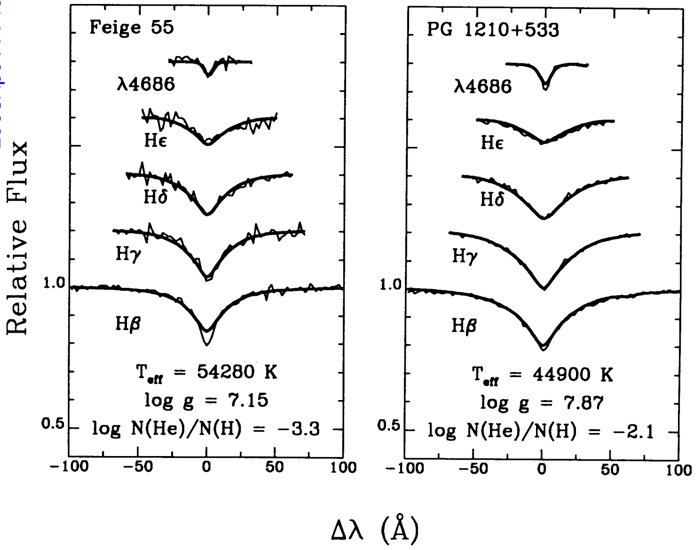

FIG. 1.—Best fit to the Balmer and He II λ4686 lines for (*left*) Feige 55 and (*right*) PG 1210+533. The chemical composition is assumed homogeneous throughout the atmosphere.

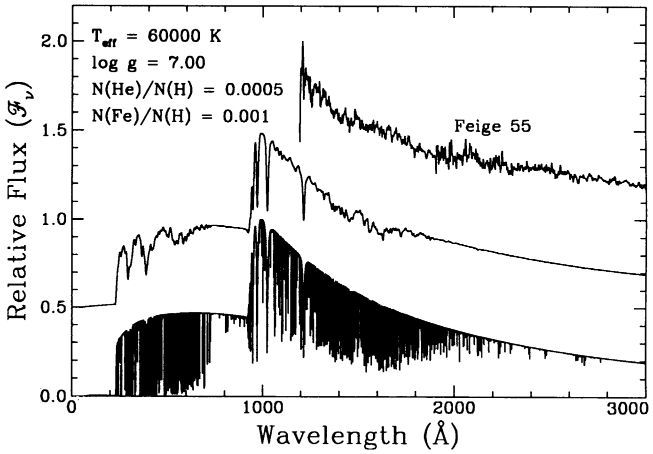

FIG. 2.—Energy distribution from one of our model atmosphere calculation (*bottom*). Only the regions where blanketing by iron lines is important are displayed. Also shown is the same energy distribution convolved with a 7 Å instrumental profile (*middle*), and low-dispersion *IUE* images (SWP 31179 and LWP 11030) of Feige 55 convolved with a three-point box filter (*top*).

of the central stars of PNs observed by NS could be significantly affected by the presence of metals (Dreizler & Werner 1992a, b), is explored in a more quantitative manner in the following.

2. MODEL CALCULATIONS INCLUDING METAL-LINE BLANKETING

In model atmosphere calculations which take into account the effect of line blanketing by metallic ions, several times 10^4 transitions have to be considered simultaneously. Dreizler & Werner (1992a, b) have tackled this problem for iron in non-LTE model atmospheres using frequency-sampling techniques and a statistical approach similar to that used by Anderson (1989). Because we are mainly interested in the first-order effect of the presence of metallic ions on the temperature structure of hot DAO stars, we adopt here a simpler approach. First, we assume that iron is the only metallic ion present; the absence of other heavy elements can be compensated to some extent by varying the iron abundance. Furthermore, the atmospheric structure is considered in LTE, as are the hydrogen and iron level populations. This approximation is probably better justified in a cooler DAO star such as Feige 55 than it is for the hotter stars considered by Dreizler & Werner. Indeed, NS have shown that non-LTE effects are unimportant at Hβ below 60,000 K. The model atmospheres are calculated using a modified version of the linearized code of Wesemael et al. (1980), in which the monochromatic opacity is evaluated explicitly at each frequency points. Our sampling of only ~15,000 frequency points (for a spectral resolution of 0.2 Å in the UV region) remains insufficient to reproduce correctly each individual iron line profile. However, since we are interested only in the global effect of line blanketing on the atmospheric structure, we can simply compensate the lack of frequency resolution by adjusting the iron abundance to make the lines, and therefore the *total* line opacity, weaker or stronger.

Our treatment of the atomic level structure and line broadening of iron is similar to that outlined in Vennes et al. (1992). In particular, we include all lines of Fe III–VII for which theoretical oscillator strengths are available from the tables of Fawcett (1989). Synthetic spectra calculated with a 0.01 Å resolution are identical to those displayed in Vennes et al. (1992). The energy distribution from one of our model calculation is displayed in Figure 2 for an iron abundance of $N(\mathrm{Fe})/N(\mathrm{H}) = 0.001$. We also compare the same energy distribution, convolved with the 7 Å instrumental profile of the *IUE*, with two archival low-dispersion *IUE* images of Feige 55. The integrated opacity of iron lines is certainly as important as that of the Lyman series of hydrogen in the UV region. Furthermore, the iron contribution to the total opacity is also significant in the EUV regions. The presence of heavy elements is the most likely cause of the EUV and soft X-ray flux deficiency in hot white dwarf stars (see below).

Figure 3 illustrates the effect of varying the iron abundance

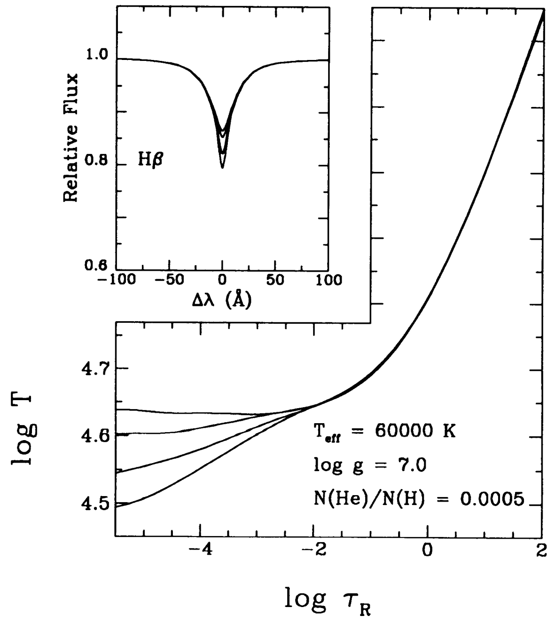

FIG. 3.—*Lower right panel:* Temperature stratification of models with various iron abundances of (*top to bottom*) $N(\mathrm{Fe})/N(\mathrm{H}) = 0$, 10^{-5}, 10^{-4}, and 10^{-3}. *Upper left panel:* Hβ line profiles for the same model atmosphere and iron abundances; the line core gets deeper with increasing iron abundances.

on the temperature stratification of a given model. The corresponding effect on the line profile of Hβ is displayed as well. As expected, the additional line blanketing reduces significantly the temperature where the iron lines are formed. Since the cooling affects only the optically thin regions ($\tau_R \lesssim 10^{-2}$), however, the backwarming effect on the temperature structure of the deeper layers remains small, without being negligible (see below). On the other hand, the core of the Hβ line is formed sufficiently high in the atmosphere ($\tau_R \sim 10^{-3}$) that the cooling of the model in the upper layers produces a significant deepening of the line core. The higher Balmer lines (not shown here), which are formed deeper in the atmosphere, are less affected.

3. RESULTS AND IMPLICATIONS

The effect of iron-line blanketing on the predicted Hβ profile is in qualitative agreement with the observed spectrum of Feige 55 displayed in Figure 1. We have obtained a more quantitative fit to the line profiles by calculating a small grid of models around the estimated atmospheric parameters of Feige 55. Iron abundances of $N(\mathrm{Fe})/N(\mathrm{H}) = 10^{-5}$, 10^{-4}, and 10^{-3} were considered, and the optimal T_{eff} and $\log g$ values have been obtained from our best fit to the observed line profiles. We assumed that the helium abundance of Feige 55 was similar to that inferred from the zero-metal models (e.g., Fig. 1); this assumption can be verified a posteriori from the quality of the fit to the He II λ4686 line. Our best fit to the Balmer line profiles of Feige 55 is achieved with an iron abundance of $N(\mathrm{Fe})/N(\mathrm{H}) = 10^{-3}$, and this solution is displayed in Figure 4. Since the fit to the He II λ4686 line is still acceptable, we conclude that the helium abundance determination has not been affected.

The line core of Hβ calculated from the iron-blanketed model is in much better agreement with the observed profile, while the fits to the higher Balmer lines remain essentially unaffected. The iron abundance inferred from our best fit *must not* be taken at face value, however. Indeed, the number of iron lines included in our calculation is, if anything, a lower limit to the true number of iron lines present in the spectrum. Furthermore, as discussed above, our frequency sampling is too coarse, and other sources of metallic opacities have been neglected in our calculation. The determination of the iron abundance, or any other heavy element for that matter, can be performed only from a detailed analysis of individual metal line profiles. Since these lines are formed in the upper atmosphere, their profiles will be strongly dependent on the temperature stratification of the upper layers; this result emphasizes the importance of detailed metal-line–blanketed model calculations such as those currently being developed by Dreizler & Werner (1992a, b).

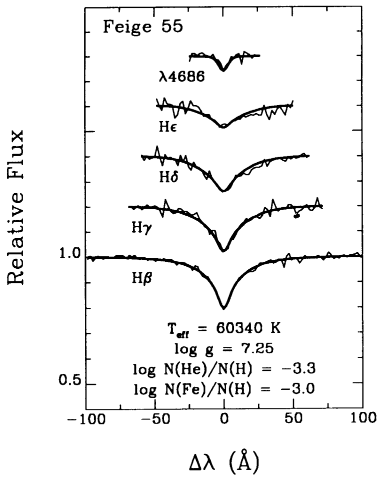

FIG. 4.—Best fit to the Balmer and He II λ4686 lines for Feige 55 using model atmospheres where iron-line blanketing is taken into account.

Despite the uncertainties inherent to our calculations, our results clearly confirm that the presence of metallic ions in the photosphere of Feige 55 is at the origin of our poor initial fit to the Hβ line displayed in Figure 1. These ions provide enough opacity to cool the upper atmospheric layers; the line core of Hβ, and to a much smaller extent those of the higher Balmer lines, are predicted to be deeper. Consequently, fits to the line profiles of hot DA and DAO stars using zero-metal abundance models can be used to *infer* the presence of metals in these stars. From our best fit to the line profiles of PG 1210+533, for example, it can be readily concluded that the abundance of metallic ions is probably low, in agreement with the results of the *IUE* observations of Holberg et al. (1987, 1988). A closer examination of the Hβ line core, however, reveals that the fit is not perfect and that small traces of metallic ions, while still remaining undetectable in high-dispersion *IUE* observations, could improve the quality of our fit.

Analyses of soft X-ray observations of hot DA stars show that, in the objects where heavy elements are visible in the *IUE* spectrum, absorption by metals is the most likely cause of the observed EUV and soft X-ray flux deficiency. In the remaining objects, which are not found to show metal lines in the FUV, the observed high-energy flux deficiency is attributed either to smaller metal abundances or to helium stratification in the atmosphere (Vennes & Fontaine 1992, and references therein). In the light of the growing interest of these analyses, the results presented in this *Letter* demonstrate that careful, but nevertheless standard, line fitting in the optical represents a powerful tool to discriminate whether helium or heavy elements are the likely cause of the observed flux deficiency at high energies.

As part of an ongoing analysis of the properties of hot DA and DAO stars, we have found many other objects showing the Hβ symptoms observed in Feige 55. For those stars, which include LS V+46 21, the presence of metallic ions is likely to be responsible for the discrepant fits as well. It remains unclear, at the moment, why the abundance of metallic ions in DAO stars such as Feige 55 is higher than in other stars such as PG 1210+533. The atmospheric parameters given in Figure 1 suggest that a surface gravity which is lower than average could perhaps lead to an atmosphere polluted with larger traces of metals. Preliminary results by one of us (P. C.) indicate that this trend is indeed what is predicted qualitatively from radiative acceleration calculations. However, whether radiative acceleration is *sufficient* to support the observed abundance of iron or other heavy elements currently remains an open question.

The results of Figures 1 and 4 indicate that the temperature determination, and to a lesser extent the surface gravity determination, are significantly affected by the presence of heavy elements in the atmosphere. This result is a consequence of the small backwarming effect in the regions where the continuum is formed. For Feige 55, the value of T_{eff} has increased by ~6000 K in going from a metal-free fit to one including metal ions. Since the studies of X-ray and EUV fluxes make use of atmospheric parameter determinations based mainly on optical line profile analyses, our results stress once again the importance of taking into account the presence of metallic ions in the model atmosphere calculations.

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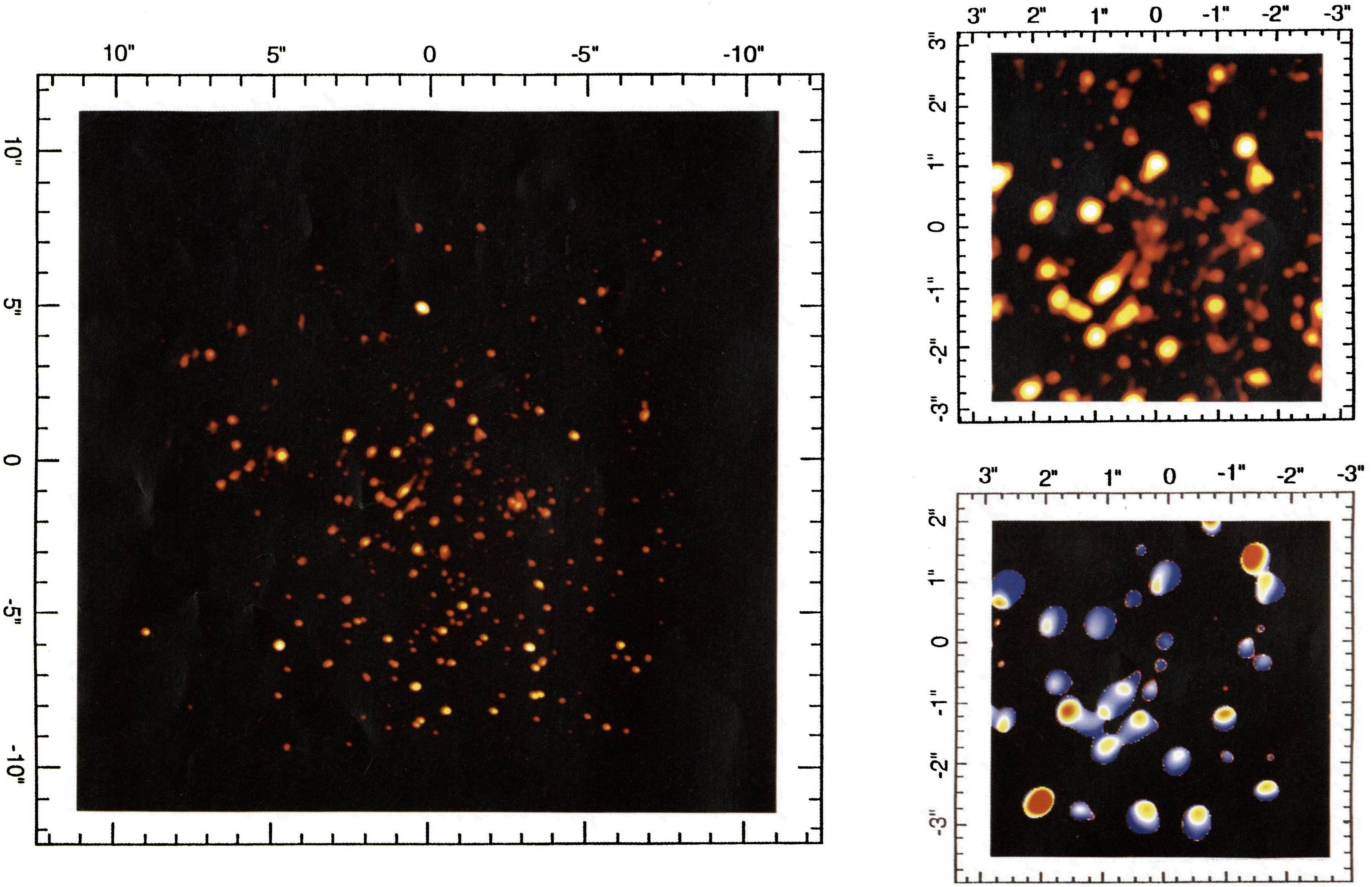

FIG. 2.—*Left:* False color representation of the speckle image reconstruction for $K \leq 14.5$ sources in the central 20″ × 20″. The spatial resolution is 0.″15 FWHM. Offsets are from the strongest (western) component of the infrared counterpart of Sgr A*. *Top right:* false color map of $K \leq 15$ sources in the most sensitive central 6.″4 × 6.″4 of the Galactic center region. The spatial resolution is 0.″15 FWHM. *Bottom right:* $H-K$ color map of the central 6.″4 × 6.″4 of the Galactic center region. The map was obtained by aligning the K- and H-band maps on a subpixel level and matching their spatial resolutions to 0.″3. Blue colors correspond to λ^{-2} spectra ($H-K \approx 0.0$ with $A_K = 3.4$, $A_H = 5.4$, Rieke et al. 1989). Red colors ($H-K \approx 1.0$) correspond to flat spectra. The H-band image used for the $H-K$ color map in Fig. 2 contains 4000 frames and has a resolution of 0.″3 and limiting magnitude of 15.

ECKART et al. (see 407, L77)