Appendix A

Background and Stellar Properties of Herbig Ae/Be Stars

A.1 Historical Information

The youngest known, optically visible, high-mass stars are the pre-main sequence Herbig Ae/Be population. These stars were first classified as a group by Herbig (1960) as the result of his search for the higher-mass counterparts to pre-main sequence stars of low-mass, the T Tauri stars . Herbig's criteria for selecting candidate objects included: 1) a spectral type earlier than F0, in order that the objects be candidate progenitors of main sequence A and B stars; 2) the appearance of Balmer series emission lines in the stellar spectrum, in order that their spectroscopic appearance be closely similar to that of T Tauri stars ; 3) a projected location within the boundaries of a dark interstellar cloud, in order to maximize the likelihood of selecting young stars still in close proximity to their presumed birthplaces; and 4) the illumination of a bright reflection nebula, in order to guarantee physical association of the star with its encompassing dark cloud. Application of these criteria resulted in the selection of 26 candidate young, intermediate mass pre-main sequence stars. The pre-main sequence nature of many of the Ae/Be was confirmed by Strom *et al.* (1972) who placed a subset of the original list of objects in the Hertzsprung-Russell (HR) diagram, and derived ages and masses ranging from 0.1 to 1 Myr and from 1.5 to 15 $M_{\odot}$, respectively. Finkenzeller & Jankovics (1984) compared stellar radial velocities for a sample of Ae/Be with the velocities measured for nearby molecular material, and confirmed the physical association of these stars with their presumed parent clouds.

Subsequent work has shown that most of Herbig's Hα -selected population do, in fact, share a number of characteristics in common with the T Tauri stars: large infrared, submillimeter and millimeter continuum excesses indicative of a significant mass of circumstellar dust located over a wide range of distances from the central star; optical and ultraviolet metallic emission lines as well as strong Balmer emission lines, some showing the P Cygni features indicative of energetic mass outflows; centimeter-wave radio continuum emission, perhaps tracing the ionized component of such outflows; location near the center of high-velocity CO gas, apparently accelerated by the energetic outflows diagnosed from optical spectra; and rapid photometric, spectroscopic, and in some cases polarimetric variability (see Catala (1989) for a review).

A.2 Techniques for Determining Stellar Parameters

As discussed in the main text, pre-main sequence stars are complicated objects for which to derive intrinsic stellar parameters. Observational uncertainties are introduced by high levels of interstellar and circumstellar extinction, as well as by both line and continuum flux excesses due to circumstellar activity. Theoretical uncertainties are introduced by the complexity of the physical processes associated with accretion and pre-main sequence evolution, as well as by the rapidity with which these processes occur, particularly for high-mass stars such as are our focus here.

We have two (related) quantitative methods of estimating stellar masses and ages during the pre-main sequence phase 1) from the location of a star in the theoretical HR diagram, and 2) from a measured surface gravity. Both depend on a combination of observation and stellar evolutionary theory.

First, we can locate the star in the H-R diagram and compare its position to theoretical pre-main sequence evolutionary tracks and isochrones. Interpolation

between the computed tracks yields an estimate of the stellar mass and age. To locate the star in the H-R diagram, we first determine its effective temperature via the presence/absence of temperature-sensitive photospheric absorption features in optical spectra. We then find the intrinsic colors of a star corresponding to that effective temperature, and determine the color excess via comparison with the observed colors of the star. All of the color excess is attributed to reddening. With an assumed extinction law which relates selective extinction to total extinction at a particular wavelength, we then correct an observed magnitude for reddening. We must be careful at this step to choose a wavelength regime which measures primarily photospheric continuum, and which is not sensitive to either disk emission or boundary-layer emisison. For early-type star/disk systems, 0.55 μm(V-band) and 0.64 μm(R-band) are generally good choices. The bolometric magnitude of the star is determined by adjusting the reddening-free magnitude for distance, and then for its bolometric correction (also determined from the effective temperature). Finally, the stellar luminosity is calculated using $L/\ \mathrm{L}_{\odot} = 10^{-0.4(\mathrm{M_{bol}}-4.83)}$. The superposition of pre-main sequence evolutionary tracks on a plot of log $(L_*/L_{\odot})$ versus log T_{eff} can be used to estimate stellar masses and Kelvin-Helmholtz stellar ages (*n.b.* see discussion in Chapter 8 on the applicability of Kelvin-Helmholtz ages to high-mass stars). Because of the rapid evolution of high-mass stars, however, age resolution is particularly difficult.

A second method for estimating stellar masses and ages relies on surface gravity determinations. Instead of combining spectroscopic information with photometric information and using assumed standard relationships to derive stellar luminosities, location of a star in the log g - log T_{eff} diagram depends only upon spectroscopic measurements. The method therefore avoids any ambiguities introduced by distance uncertainty, photometric variability, by uncertainties in the reddening law, or by contamination of photospheric continuum by disk or

boundary-layer emission (although the veiling of absorption lines could be a source of error). If the surface gravity of a star is smaller than the surface gravity of main sequence star with the same effective temperature, then the star is a pre-main sequence star of higher mass than that suggested by the effective temperture. Interpolation between evolutionary tracks on a log g versus log T_{eff} diagram then yield stellar masses and ages. Low surface gravities suggest maximum limits on stellar ages based on the Kelvin-Helmholtz pre-main sequence contraction time for a star of that mass.

A.3 A New Spectroscopic Analysis

In order to effect the above procedures and derive masses and ages for Ae/Be stars, a modern set of classification-resolution spectra was required. Medium-resolution ($R \approx 4000$) spectra of 29 Ae/Be stars were obtained by LAH and S. Strom at Kitt Peak National Observatory with the 2.1m telescope, GoldCam spectrograph and the F3KA CCD. The wavelength coverage was 3745 - 5180 Å at 0.47 $\AA$ / pixel^{-1}.

The spectra were first used by L. Ghandour to derive spectral types and rotational velocities for the Ae/Be stars. Spectral types were determined primarily from He I , He II , Fe I , and Ca I lines. Rotational velocities were determined by interpolating between grids of slowly rotating standard stars (obtained during the same run as our target stars) whose spectra were artificially broadened according to the rotation profile (Gray 1992, p. 374)

$$G(\delta\lambda) = \frac{2(1-\varepsilon)[(1-(\delta\lambda/\delta\lambda_L)^2]^{\frac{1}{2}} + \frac{1}{2}\pi\varepsilon[(1-(\delta\lambda/\delta\lambda_L)^2]}{\pi(1-\varepsilon/3)},$$

where $\delta\lambda_L$ corresponds to the doppler shift at the stellar limb and is equivalent to v sin$i$. The standard star spectra were artificially rotated in bins of 25 km s^{-1}, and matched to the object spectra in the wavelength regions containing the He I λ4471 Å and Mg II λ4481 Å lines.

A.4 Surface Gravities

For F, G, and K stars, the surface gravity of a star controls all pressure effects in a stellar spectrum, and measuring surface gravity is then equivalent to measuring pressure. For earlier type stars, however, the usual pressure diagnostics may not be produced by pressure effects alone (see discussion below). The difficulty is in finding pressure-sensitive spectral features. While temperature changes of a few tens of percent are clearly noticeable in comparisons between stellar spectra, changes in surface gravity of a few hundreds of percent are required in order to produce effects of similar magnitude. Typically, for hot stars, the size of the Balmer discontinuity (A and F stars) or the residual intensity of Balmer-line wings are used as gravity indicators. (He I and He II are also used as gravity indicators for O-type stars, but theoretical calculations of broadened line profiles are not as consistent with the observations for the He lines as they are for H I lines.) Balmer lines are pressure-sensitive when they are strong, that is, for early type stars. Once a spectral type and a rotational velocity have been established for a star, as we have done, the strength of the hydrogen wings is attributed to Van der Waals and Stark broadening Pressure-broadening is measured by quantifying the residual line intensity as a function of distance from line center, and comparing it to theoretical models. Assuming a conversion from pressure-dependence to surface-gravity-dependence of spectral features therefore measures the effective gravity required in hydrostatic equilibrium.

With temperatures and rotational velocities estimated from helium and metallic lines, we could then determine surface gravities for Ae/Be stars using the $H\beta$, $H\gamma$, and $H\delta$ lines. These lines are in general free of the emission components which characterize many of the Hα profiles in Ae/Be stars, although in some cases there is core emission at $H\beta$. From the residual intensities at 10 and 12 $\AA$ displacement from line center, we assigned a surface gravity based on comparison

to the grid of LTE model atmospheres calculations of Kurucz (1979). The largest source of error in this method is in assigning the continuum level, which we do by low-order polynomial fitting. An error of 5% in residual intensity translates into an error of a few tenths in log g for an A0 star. Even if the star is rotating at 400 km s^{-1}, the doppler shift expected at 4200 $\AA$ is only 5.5 $\AA$; thus our surface gravity estimates are not affected at all by rotational broadening.

The stellar parameters given in Table 1.1 are derived from the new data and methods presented in this Appendix. In the cases where we do not possess updated information, we take spectral types from the literature and calculate stellar parameters as described in Hillenbrand *et al.* (1992).