THEORETICAL STUDIES OF CHROMOSPHERES AND WINDS IN COOL STARS

Grant NAGW-511

Semiannual Progress Report No. 4

For the period 1 April 1985 through 30 September 1985

Principal Investigator

Dr. Lee Hartmann

January 1986

Prepared for
National Aeronautics and Space Administration
Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Dr. R. E. Stencel - Code EZ-7, Headquarters, National Aeronautics and Space Administration, Washington, D.C. 20546.

THEORETICAL STUDIES OF CHROMOSPHERES AND WINDS IN COOL STARS

Grant NAGW-511

Semiannual Progress Report No. 4

For the period 1 April 1985 through 30 September 1985

Principal Investigator

Dr. Lee Hartmann

January 1986

Prepared for
National Aeronautics and Space Administration
Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Dr. R. E. Stencel - Code EZ-7, Headquarters, National Aeronautics and Space Administration, Washington, D.C. 20546.

I. Winds and Envelopes of Evolved Stars

We have begun to explore the propagation of pulsational waves through the atmosphere of the M supergiant α Ori. We are using a a version of the Boris and Book (1973, 1976) time-dependent hydrodynamic code modified by S. Habbal. Exploratory pulsation calculations for isothermal atmospheres have been completed; this approximation should not be too bad for evaluating the dynamics of the inner envelope (Wood 1979; Willson and Hill 1979). The models were computed using an Eulerian scheme. An innovative feature of these models is the inner boundary condition. A body force was invoked whose location varies in radius, producing shock waves of a given period. We fix the inner boundary density and temperature, but adopt a "flow-through" boundary condition for the velocity, so that mass loss may occur freely.

As shown in Figure 1, one particular model with a pulsation period of about one year produces shock velocities of 30 km s^{-1} near the surface, decaying to about 10 km s^{-1} at about 2 stellar radii. (Although the nominal mean period of α Ori is suggested as $\sim$ 5 yr [Goldberg 1979], the star exhibits substantial variations in optical light and polarization on timescales of a year or so [Guinan 1984]). Figure 2 demonstrates the effect of lowering the assumed wind temperature from 10^4K to 5000K. The density falls off much more rapidly owing to the reduced thermal support. The shock velocity increases by only about 30%, encouraging us to think that reasonable shock velocity predictions can be made without accurately establishing the wind temperature.

Our calculations are suggestive in view of steady planar shock models computed by J. Raymond. The Ca II/Mg II ratio seems to be an excellent diagnostic of shock velocity, running from 14.7 at $V_s = 10$ km s^{-1} to 0.16 at 40 km s^{-1}. As shown in Table 1, the observed Ca II/Mg II ratio is reproduced for a shock velocity $\sim$ 20 km s^{-1}, and is much more consistent with the observations than our previous homogeneous model (Hartmann and Avrett 1984). A small number of shocks in the envelope at densities $\sim 10^{10}$ cm^{-3} would produce fair agreement between calculated and observed line strengths (except for [C II, which is collisionally deexcited at large densities).

II. FU Orionis mass loss

Herbig (1977) argued that the progenitors of the FU Orionis eruptive variables are low-mass T Tauri stars. In outburst, FU Ori objects become $> 10^2$ times more luminous than in the pre-eruption state, and the decay timescales for the outbursts can be years to decades (Herbig 1977). This large luminosity increase, plus the observation of P Cygni profiles in lines of low-abundance species such as Na I (Herbig 1966, 1977; Bastian and Mundt 1985) suggests that FU Ori objects have mass ejection rates far in excess of such rates for T Tauri stars, and may therefore have a significant impact on the surrounding interstellar medium.

In a paper just completed (Hartmann, Croswell, and Avrett 1986), we determined wind properties for three FU Orionis objects using radiative transfer models primarily based on optical line profiles. Detailed radiative transfer and statistical equilibrium calculations were performed using the Pandora non-LTE code Avrett and Loeser 1984). We adopted a three-level model hydrogen atom, and an eight-level neutral sodium model atom to model the observed Hα and Na I resonance line profiles. Because the wind temperature structure is unknown, we constructed a grid of isothermal steady-flow wind models with different temperatures and mass loss rates for a particular assumed velocity distribution. Although there is no reason to suppose that these winds are isothermal, such a grid conveniently summarizes the temperature sensitivity of different species, and suggests the effects that non-isothermal distributions might have on the results. By modelling lines with different excitation properties, we were able to constrain the range of mass loss rates and wind temperatures by obtaining acceptable fits to the observed line profiles.

The basic wind model has a temperature in the wind of 5000K and a rather high mass loss rate of 5 x 10^{-5} $M_{\odot}yr^{-1}$. As shown in Figures 3 and 4, the isothermal model roughly reproduces the Hα and Na I line profiles in FU Ori. The radial velocity in this model accelerates rapidly near the stellar surface in order to provide the required occultation of redshifted (P Cygni) emission.

The principal discrepancies between observation and theory are that the predicted Na I absorption isn't quite deep enough at low velocities, and there is too much Hα absorption predicted just redward of line center. Relaxation of the isothermal assumption would make it easier to reproduce the line profiles in detail. However, there is little reason to attempt to improve the fit between model and observation from the point of view of determining mass loss rates. As we show below, plausible changes in the geometry and velocity field of the outflow can change the derived mass loss rate by an order of magnitude. The level of agreement shown in Figures 3 and 4 is clearly adequate for such accuracy.

We next considered the effects of varying the wind temperature, keeping the velocity field fixed. If a different wind temperature is adopted, a different mass loss rate must be adopted in order to produce the same line profile. Since the Na I and Hα line profiles are produced primarily by scattering of photospheric radiation, with little thermal contribution from atomic collision processes, the problem essentially reduces to maintaining the same populations in the ground states of Hα and Na D_1, D_2 (and therefore the same line optical depths at a given velocity).

We found that we could make reasonably accurate, simple estimates of the required relationship between wind temperature and density or mass loss rate, guided by the detailed Pandora results. The results of this scaling are shown in Figure 5. For higher wind temperatures, the mass loss rate required by Hα is greatly diminished. On the other hand, Na I is much less temperature sensitive than Hα. Figure 5 indicates that these simple estimates for the mass loss rates required by the Hα and Na I profiles diverge at temperatures higher than 5000K. This behavior is substantiated by our detailed Pandora calculations.

We also considered the effect of changes in the adopted velocity law. In order to provide sufficient occultation of the red-shifted emission, the previously adopted velocity increased to 180 km s^{-1} at a distance of 0.16 R_* above the surface. However, it is not clear that this geometry is appropriate. Recently, we suggested (Hartmann and Kenyon 1985) that FU Orionis eruptions are the result of massive accretion from a disk onto a T Tauri star. This model is able to explain a variety of observational peculiarities of FU Orionis objects. With this model one can imagine alternatives to the velocity structure adopted above. The wind might be spherically symmetric, but the disk could provide occultation of red-shifted emission far beyond the "photosphere". Or, the wind might arise from the surface of the luminous disk itself. In this case the flow might be naturally "bipolar" rather than spherically symmetric (cf. Hartmann and Kenyon 1985) and the red-shifted emission would once again be cut off by the disk. In either event, the disk occultation would permit much more slowly-accelerating velocity laws.

The dotted lines in Figure 5 show the schematic results using a velocity law which accelerates to terminal velocity over a distance comparable to the optical photospheric radius. One can see that the Hα profile can be fitted with a mass loss rate essentially one order of magnitude smaller than before. However, the mass loss rate required by the Na I profiles results decreases by a smaller amount, due to the strong density-sensitivity of Na I. (Note that the disk model requires accretion at a rate of $\sim 10^{-4}$ $M_{\odot}yr^{-1}$, so that efficiency considerations favor the slow velocity law with a mass loss rate $\sim 10^{-5}$ $M_{\odot}yr^{-1}$.

From this investigation we concluded that the winds from FU Ori objects have low temperatures (T $\sim$ 5000K - 8000K), and so are not thermally driven. FU Ori and V1515 Cyg have mass loss rates of $\gtrsim 10^{-5}$ $M_{\odot}yr^{-1}$; the mass loss rate of V1057 Cyg is estimated to be almost an order of magnitude lower. These rates are 10^2 - 10^3 times larger than the mass loss rates estimated for T Tauri stars, and are large enough to produce Herbig-Haro objects and other interstellar medium flows without special collimation to improve the efficiency. Depending on the frequency of these outbursts, mass loss from FU Ori objects may have significant effects on the interstellar medium in regions where low-mass stars are formed.

TABLE 1

LINE FLUXES (α Ori and models)

Line	Observed	Wind Model	Shock models, $V = 20$ km s^{-1}	
			$n_0 = 10^{10}$ cm^{-3}	10^8 cm^{-3}
Ly α	>75	-	1.4(4)	1.3(2)
Ca II	7.0(3)	1.1(5)	4.6(3)	2.9(1)
Mg II	1.4(4)	3.5(4)	8.4(3)	5.7(1)
C II λ2325	1.1(3)	4.8(3)	7.8(1)	1.1(1)
Si II λ1800	1.0(2)	6.8(1)	2.1(1)	0.17

Numbers in parenthesis indicate powers of ten.

References

Avrett, E.H., and Loeser, R.L. 1984, in *Methods in Radiative Transfer,* ed. W. Kalkofen, (Cambridge: Cambridge University Press), p. 341.

Boris, J.P., and Book, D.L. 1973, *J. Comput. Phys.,* **11,** 38.

__________ 1976, *J. Comput. Phys.,* **20,** 397.

Engvold, O., Kjeldseth Moe, O., Jensen, E., Jordan, C., Stencel, R., and Linsky, J. 1984, in *Proceedings of the Third Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun,* eds. S. L. Baliunas and L. Hartmann, (Berlin: Springer), p. 326.

Goldberg, L. 1979, *Quart. J. R.A.S.,* **20,** 361.

Guinan, E.F., 1984, in *Proceedings of the Third Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun,* eds. S. L. Baliunas and L. Hartmann, (Berlin: Springer), p. 336.

Hartmann, L., and Avrett, E.H. 1984, *Ap. J.,* **284,** 238.

Hartmann, L., Croswell, K., and Avrett, E.H. 1986, in preparation.

Hartmann, L., and Kenyon, S.J. 1985, *Ap. J.,* **299,** 462.

Herbig, G.H. 1977b, *Ap. J.,* **217,** 693.

Willson, L.A., and Hill, S. J. 1979, *Ap. J.,* **228,** 854.

Wood, P.R. 1979, *Ap. J.,* **227,** 220.

Figure Captions

Figure 1. Hydrodynamic calculations assuming $M_* = 15\ M_\odot$, $R_* = 1000\ R_\odot$, and $T = 10^4$K in the wind. The pulsation period is 3×10^7 s, and the body force moves with this period between 1.0 and 1.2 R_*. (a) Density, (b) velocity profiles are plotted for two times separated by about one half period.

Figure 2. Same as Figure 1, except for a wind temperature of 5000K.

Figure 3. Hα profile of FU Ori, along with the predicted profile for the $\dot{M} = 5 \times 10^{-5}\ M_\odot \mathrm{yr}^{-1}$, T = 5000K, rapid acceleration, isothermal wind model.

Figure 4. Na I profiles of FU Ori, compared with predicted profiles for the same wind model as in Figure 3.

Figure 5. Dependence of Hα and Na I absorption strengths on mass loss rate for isothermal winds. The lines indicate loci of absorption line strength in agreement with observed FU Ori line profiles. Solid lines indicate results for the fast acceleration velocity law; dashed lines indicate results for a velocity law that accelerates to the same speeds over length scales one order of magnitude larger (comparable to the photospheric radius).

Figure 1a

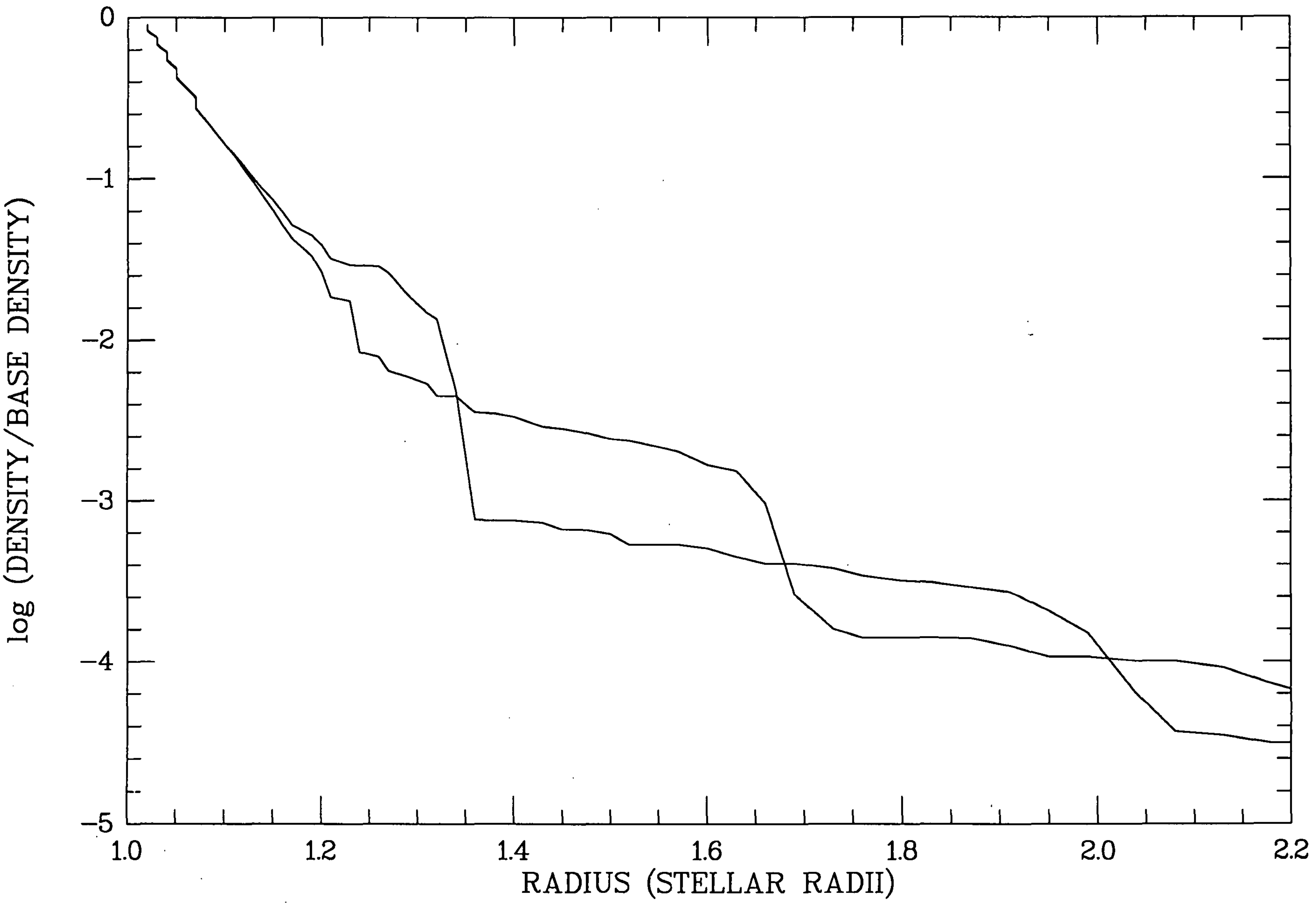
0
−1
−2
−3
−4
−5
log (DENSITY/BASE DENSITY)
1.0
1.2
1.4
1.6
1.8
2.0
2.2
RADIUS (STELLAR RADII)

Figure 1b

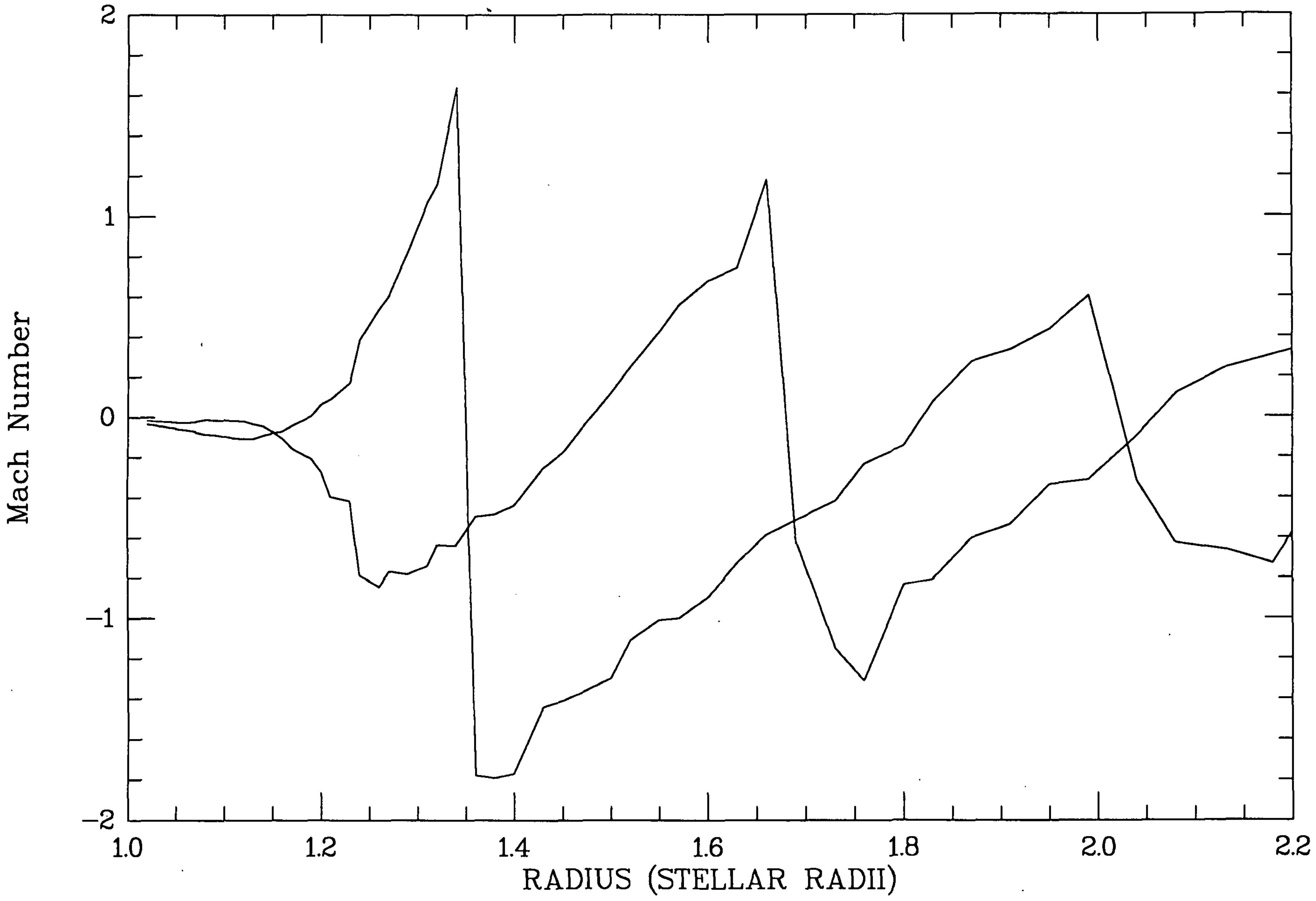

Figure 2a

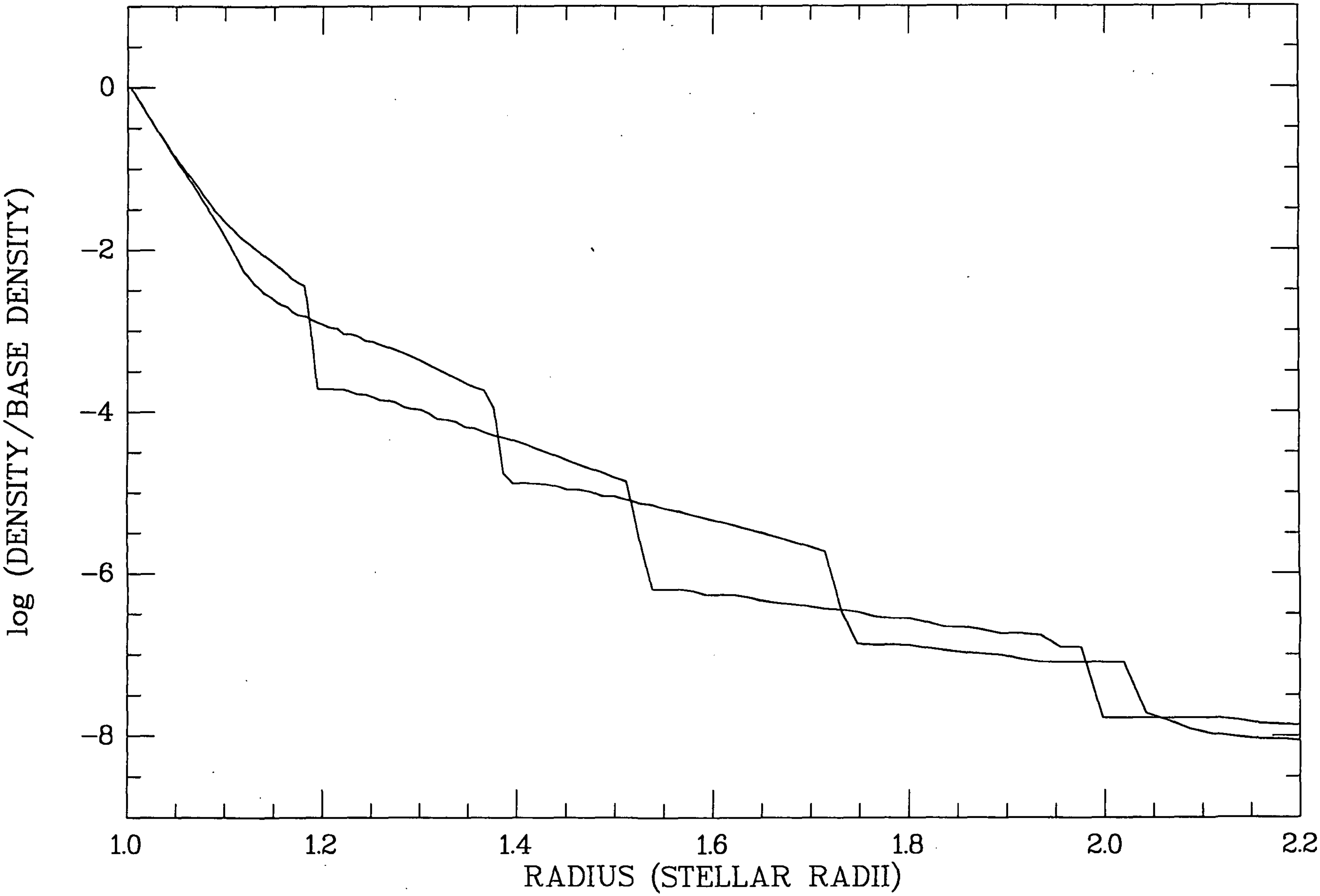
log (DENSITY/BASE DENSITY)
0
-2
-4
-6
-8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
RADIUS (STELLAR RADII)

Figure 2b

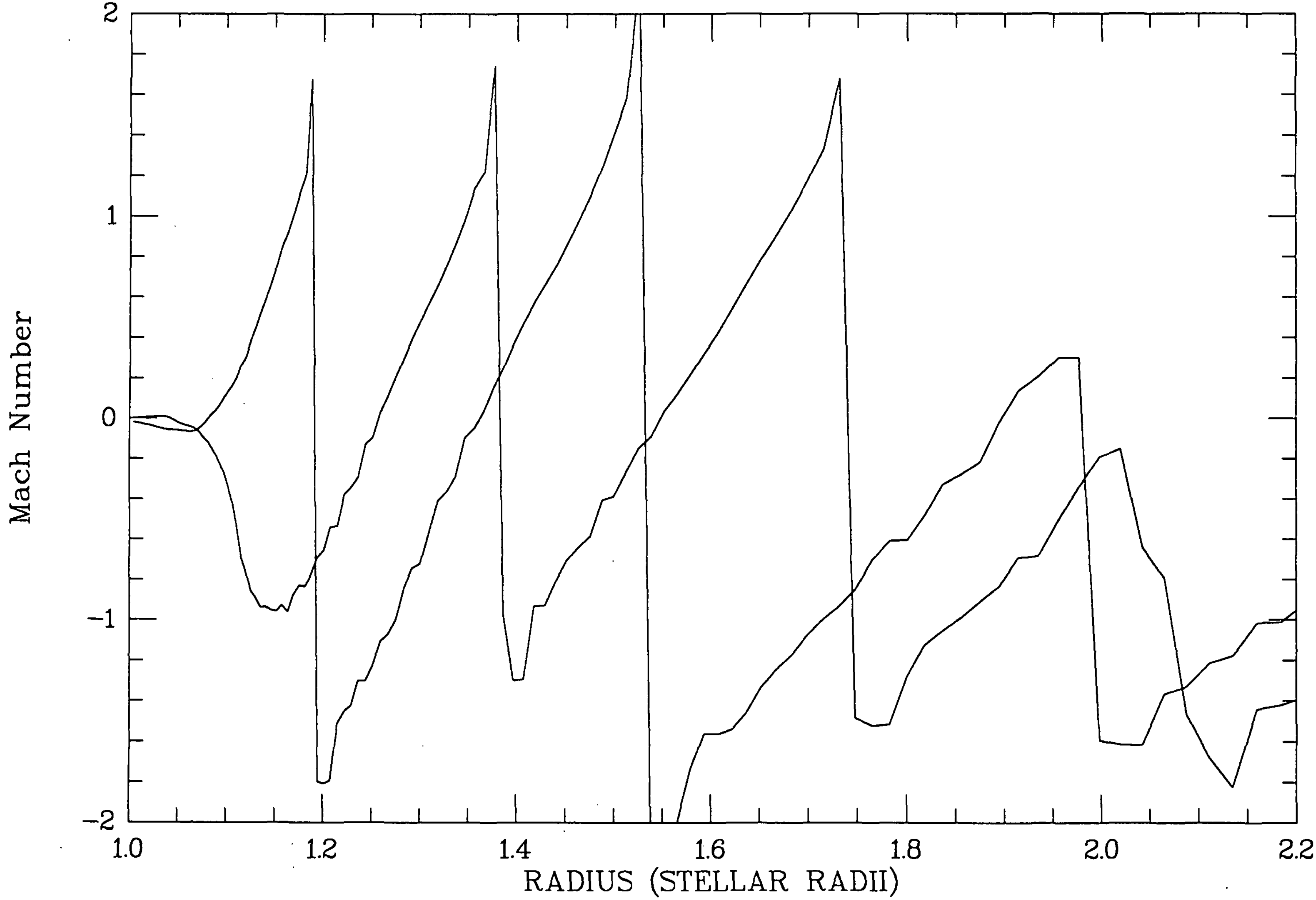

Figure 3

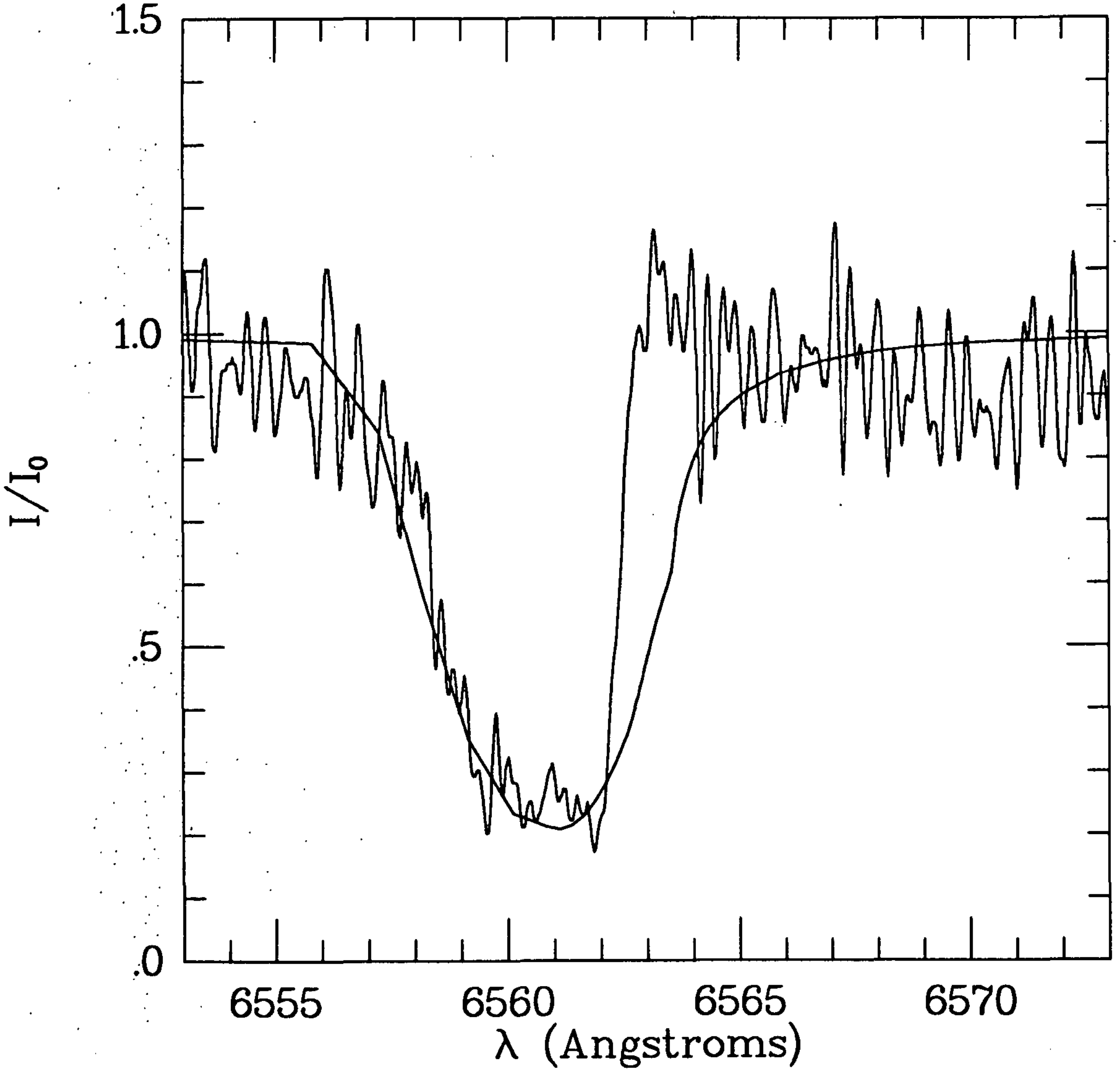

Figure 4

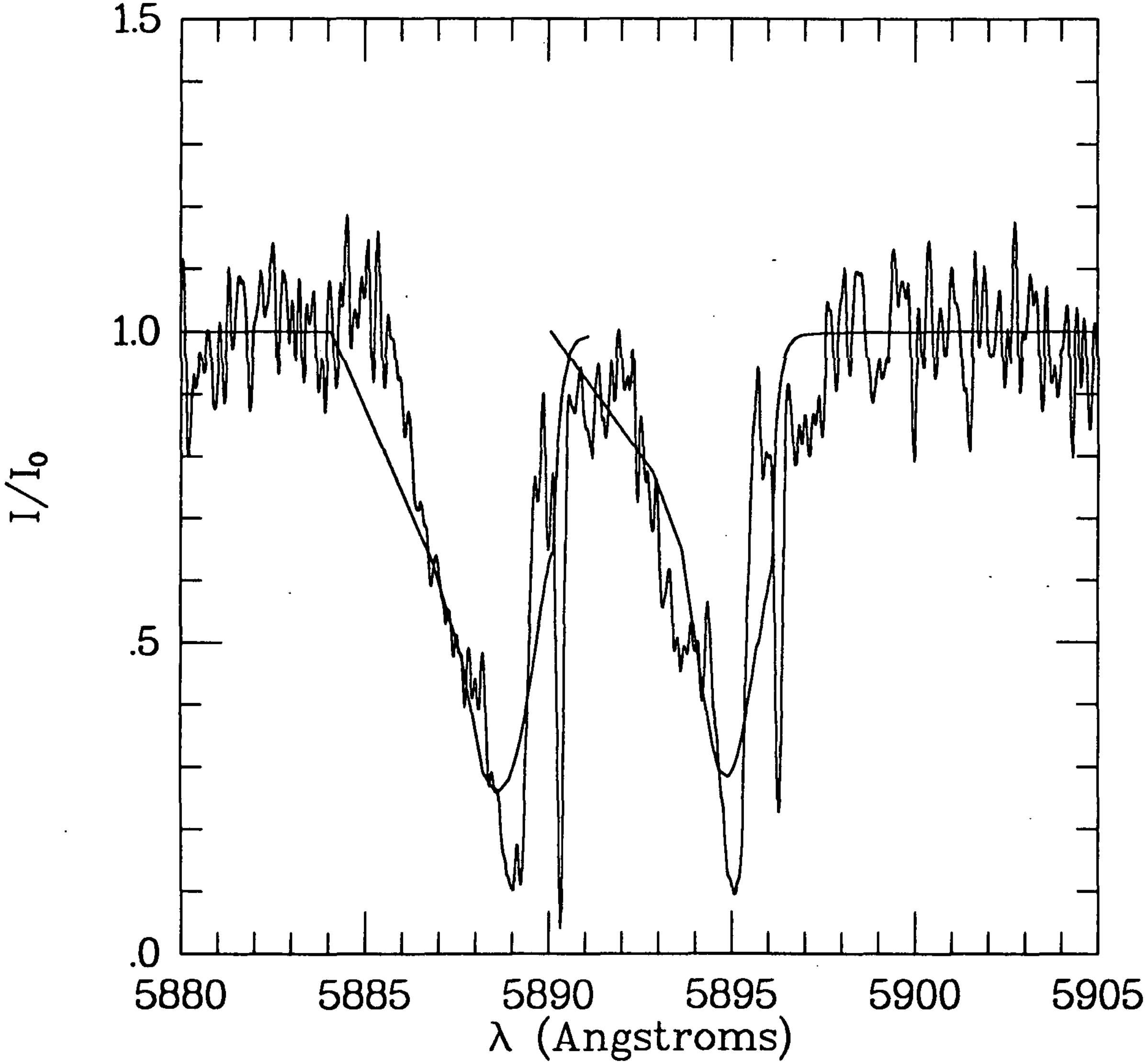

Figure 5