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APPLICATIONS OF THE MAGNETO-OPTICAL FILTER TO STELLAR PULSATION MEASUREMENTS

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ABSTRACT. A proposed method of employing the Cacciani magneto-optical filter (MOF) for stellar seismology studies is described. ~~which is different from that employed by Fossat and his colleagues in Nice.~~ The method relies on the fact that the separation of the filter bandpasses in the MOF can be changed by varying the level of input power to the filter cells. With the use of a simple servo system the bandpass of a MOF can be tuned to compensate for the changes in the radial velocity of a star introduced by the orbital motion of the earth. Such a tuned filter can then be used to record intensity fluctuations through the MOF bandpass over an extended period of time for each given star. Also, the use of a two cell version of the MOF makes it possible to alternately "chop" between the bandpass located in the stellar line wing and a second bandpass located in the stellar continuum. Rapid interchange between the two channels makes it possible for atmospheric-introduced noise to be removed from the time series.

I. INTRODUCTION

As reported recently (Fossat et al., 1983; Fossat et al., 1984; Fossat, 1985), Fossat has employed a single-cell version of the magneto-optical filter (Agnelli, Cacciani, and Fofi, 1975; Cacciani and Fofi, 1978; and Cacciani and Rhodes, 1984), to search for pulsations in α Centauri and in Pr[illegible] In this paper we will describe an alternative method of employing the magneto-optical filter (hereafter referred to as the MOF) to make such observations which should, in principle, be more sensitive and flexible than the method used by Fossat and his colleagues.

In the method of operation employed by Fossat's group a single bandpass is employed in each of the two NaD lines to transmit starlight to a photomultiplier tube. Each one of these 80 mÅ-wide bandpasses is located at the center of the corresponding D line in the laboratory frame of reference. In order to position these bandpasses at the steepest portion of the stellar Na D line profiles, Fossat and his colleagues then allow changes in the radial velocity of the star under study to shift the stellar line profile relative to the filter profiles. This type of "tuning" of the MOF relative to the stellar line means that a given star can only be observed for a very small number of nights each year. Otherwise, the changes in the earth-stellar radial velocity which are introduced by the changes in the component of the earth's orbital velocity along the direction to that star become large enough to move the two stellar D lines by a substantial amount relative to the corresponding filter bandpasses. This wavelength shift in turn means that each filter bandpass travels over such a wide range of wavelengths relative to its own width that the sensitivity of the filter to the star's radial velocity changes with time. Hence, it is not possible to employ such "orbital motion" tuning to obtain time series of more than a few days in length during which the velocity sensitivity of MOF is kept constant.

An additional problem with the use of a single bandpass at each spectral line is the difficulty of removing the scintillation noise introduced by the earth's atmosphere from the time series of intensity fluctuations transmitted through that bandpass. Even when a second detector is employed to monitor the integral starlight falling on that detector as a function of time, differences in the acquisition times of the two channels or in the location observed (in the case of so-called "dual-beam" photometers which chop against a nearby patch of the sky) can make the removal of the telluric atmospheric noise difficult. Before going on to describe the method in detail, we wish to stress that our ideas are based upon our experience gained with the MOF in the study of solar oscillations and they have not yet been tried out for the stellar case. Nevertheless, we feel that the ideas are sufficiently novel to be described here.

2. PROPOSED METHOD

During the course of evaluating the suitability of the MOF as a Doppler analyzer for the study of solar oscillations, we obtained spectral scans of the transmission profiles of the MOF for varying levels of input power and varying magnetic field strengths. These profile scans were obtained with sodium-filled MOF cells using the spectrograph of the Mt. Wilson 150-foot tower telescope.

As is shown here in Figure 1 these spectral scans indicate that the wavelength separation, the peak transmission, and the halfwidth of each filter bandpass can be altered by altering the amount of power which is input to the heater coils which vaporize the sodium. In Figure 1 we show four different spectral scans for a single Na MOF cell which was embedded in a longitudinal magnetic field having a strength of 1000 Gauss. As the input power level is increased, the two narrow bandpasses located on the sides of the Na D1 line can be seen to separate, to increase in height, and to increase in width.

The sensitivity of the wavelength separation of the two peaks to the amount of input power is summarized in Figure 2 for two different MOF cells. Here we have plotted one-half of the total peak-to-peak separation of the two bandpasses (i.e., the wavelength separation between the line center in the laboratory reference frame and one of the peaks) converted into an equivalent radial velocity measured in km/sec.

Figure 2 illustrates that the two filter bandpasses can be separated by up to 17 km/sec when the field strength is only 1000 gauss. This figure also shows that the dependence of the peak separation upon the input power is nearly linear and is very similar for both the Na D1 and D2 lines.

In Figure 3 we show that the peak transmission of the filter bandpass increases slightly with increasing input power. In Figure 4 we show that the fullwidth at half-maximum (FWHM) of each bandpass also increases as the level of input power is increased. Here the relatively small scatter in the two D1 curves suggests that the bandpasses are actually somewhat broader in D2 than they are in D1.

Figure 5 is a spectral scan of the MOF at the D1 line which is similar to those shown in Figure 1, except that here the magnetic field strength has been increased from 1000 to 6000 Gauss. This profile shows that at some power settings it is possible to get similar-appearing profiles even though the field strengths are considerably different.

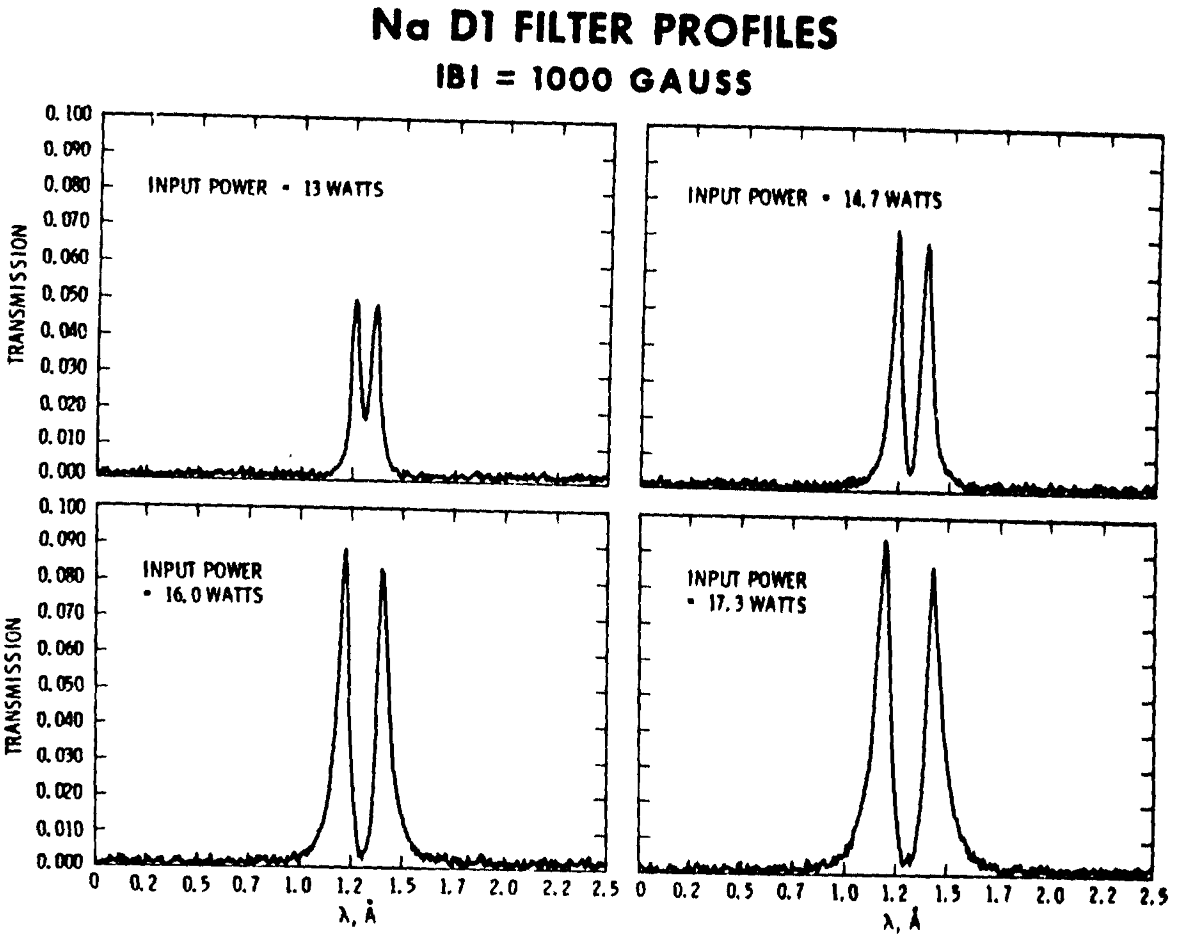

Figure 1: Transmission profile scans of the MOF in the Na D1 line. These measurements were made with the pit spectrograph of the Mt. Wilson 150-foot tower telescope. They were made for four different input power settings. A longitudinal field strength of 1000 Gauss was employed for all four scans. A single MOF cell was used in all four cases, so that one filter bandpass is shown for each wing of the Na D1 line.

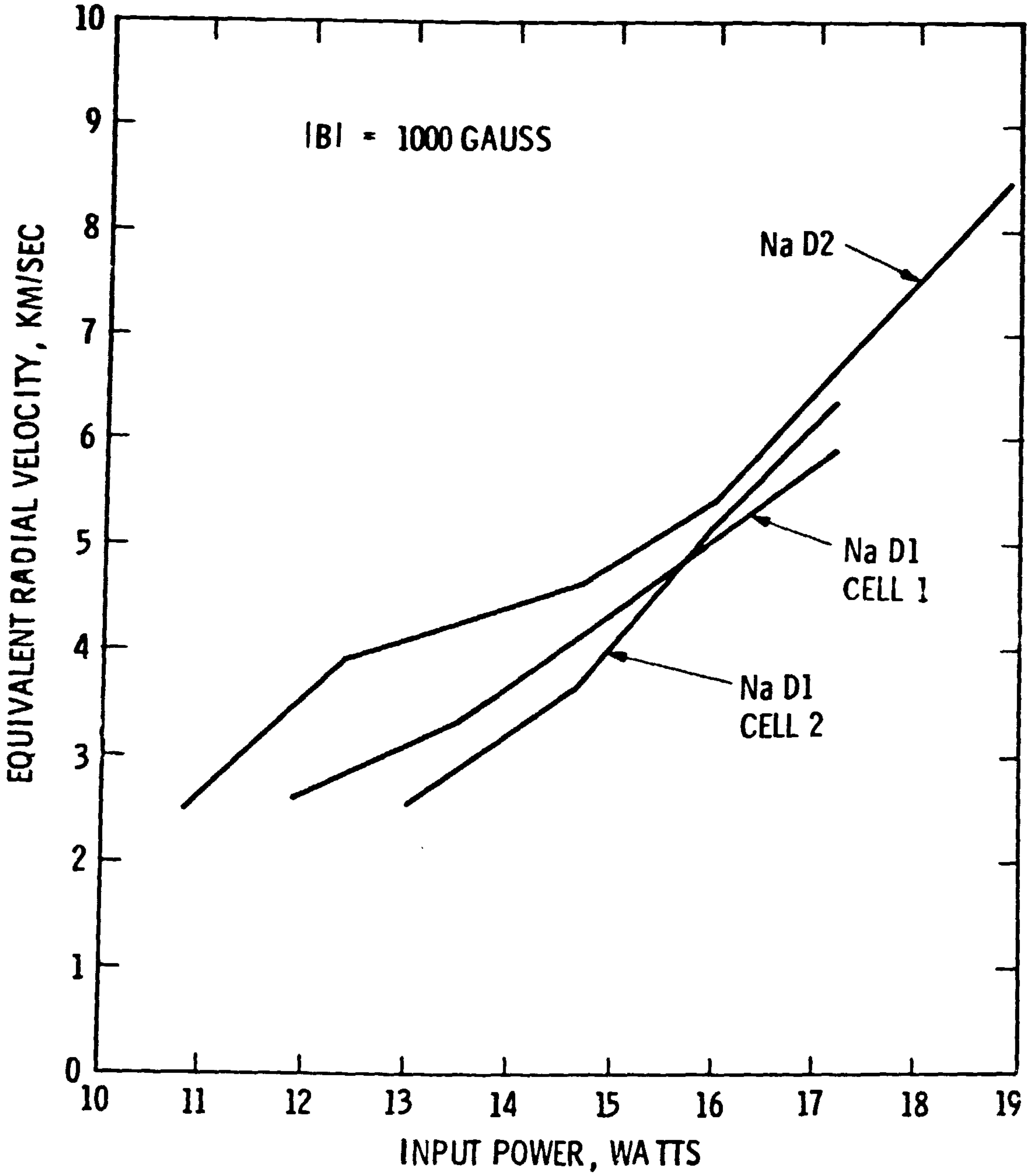

Figure 2: One-half of the peak-to-peak wavelength separations of the two transmission bandpasses is plotted here as a function of the input power applied to the cells. The wavelength separations have been converted into their equivalent radial velocities relative to the line center. The results from two different cells are shown for the D1 line, while the results from one of those two cells is also shown for D2.

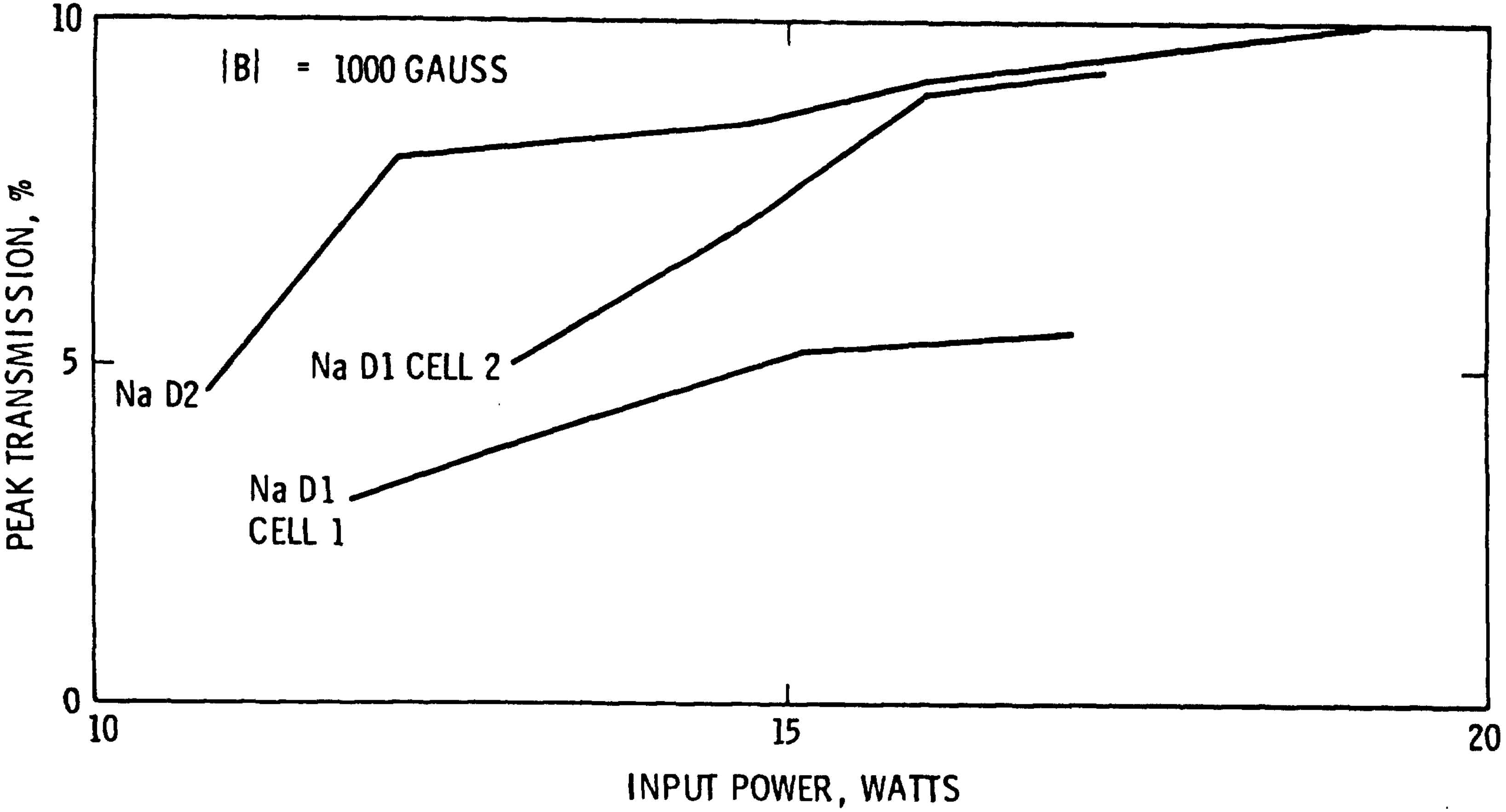

Figure 3: The percentage transmission at the peak of the MOF bandpasses shown in Figure 1 is plotted as a function of the input power applied to the cell. Also shown are similar curves for another cell at the D1 line and for cell #2 at the D2 line. The increase in transmission percentage with increasing power which was evident in Figure 1 is also seen here.

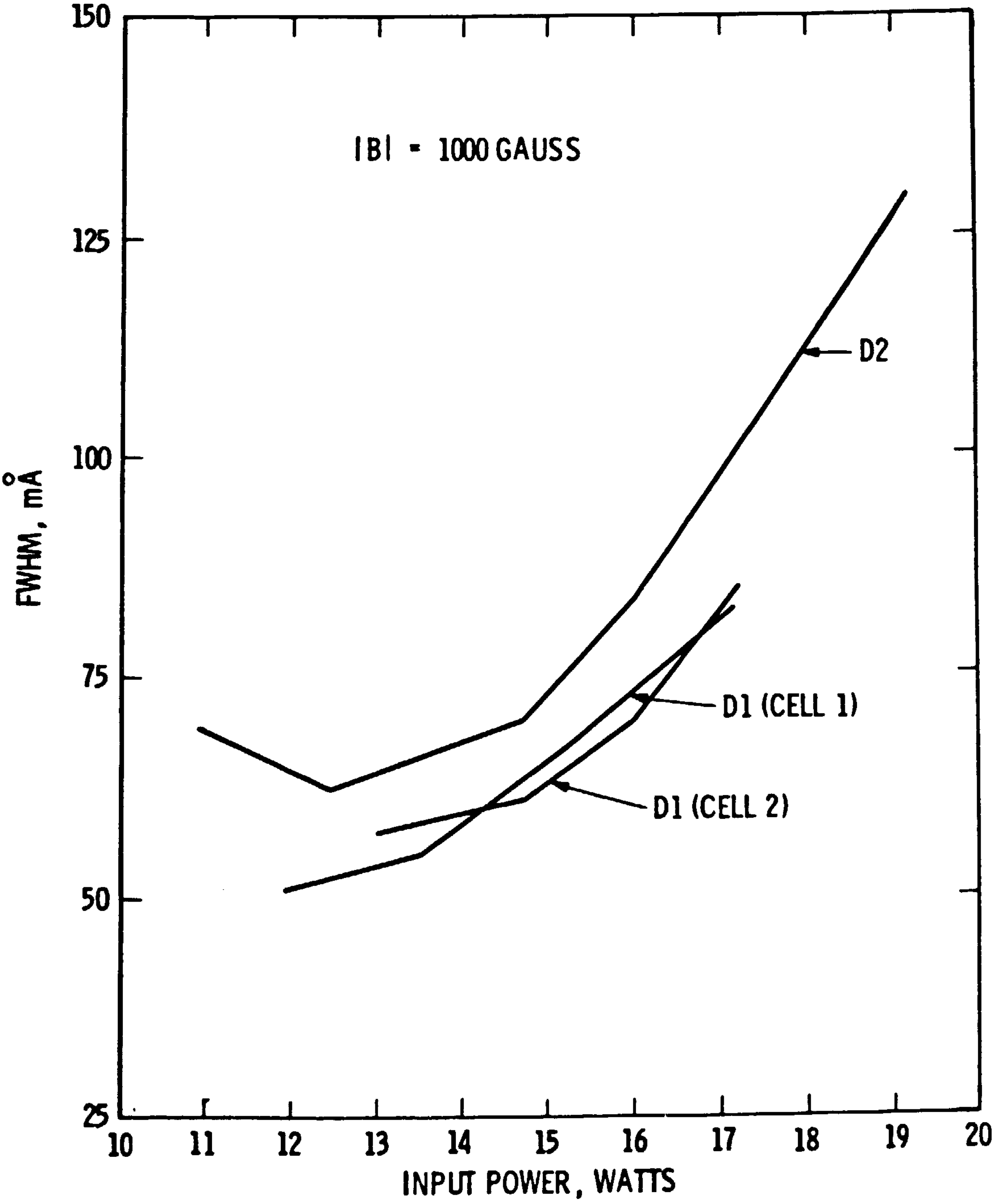

Figure 4: The fullwidth at half maximum of one of the two filter bandpasses shown in Figure 1 is shown here as a function of the input power for a field strength of 1000 Gauss.

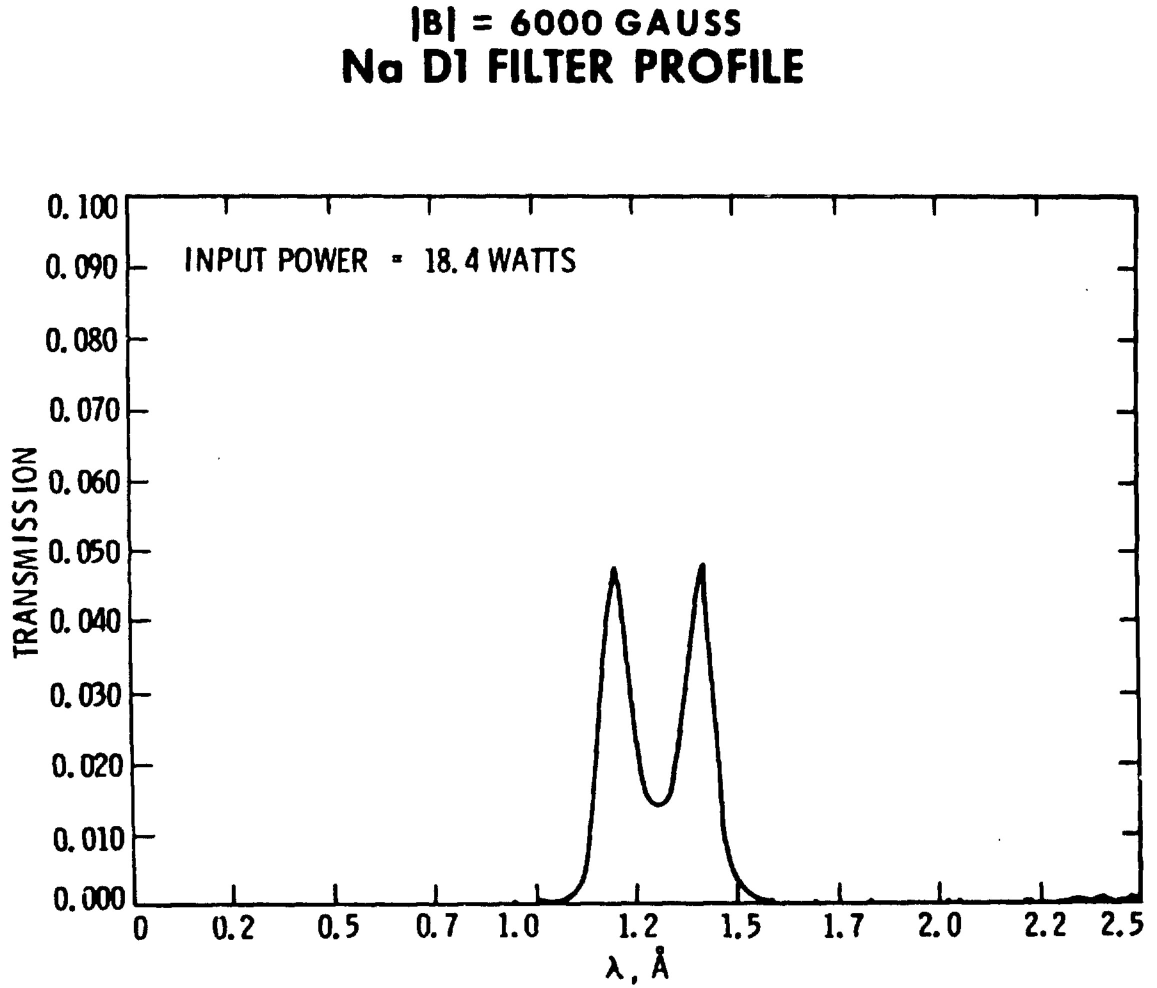

Figure 5: A transmission profile similar to those shown in Figure 1 is shown here but in this case the peak magnetic field strength was 6000 Gauss.

Figure 6, on the other hand, shows that when the input power is increased beyond a threshold level, the transmission profile of the MOF becomes more complicated. Here the individual local maxima are caused by multiple Faraday rotations of the phase of polarization of the beam within the cell. This is due to the so-called "Macaluso-Corbino Effect" described in the earlier papers on the MOF. (We note here that the end windows of the particular cell employed in the measurements shown in Figure 6 had become contaminated from operation at very high power levels and hence the peak transmission values shown of about 5% are much too low. Consequently, the vertical scale of this Figure should be ignored.)

Figure 7 shows spectral scans for the Na D2 line again at a field strength of 6000 Gauss. The two bandpasses can again be seen to move apart smoothly with increasing power and to be much cleaner than the D1 profiles shown in Figure 6.

The dependence upon input power of the center-to-peak separations of the bandpasses illustrated in Figures 6 and 7, again expressed in terms of the equivalent radial velocity of each peak from the line center, is summarized in Figure 8. Here we note that the D1 profiles can be separated by up to ± 50 km/sec from the line center by simply varying the level of power input to the cell heaters. Figure 8 shows that the tuning of the filter (at least for Na D1) is quite linear with input power and that the bandpasses can be moved to compensate for the 29 km/sec orbital velocity of the earth around the sun. Figure 8 also shows that the D2 bandpasses are not as widely separated as are the D1 bandpasses for a given level of input power.

For those stars whose heliocentric radial velocity never exceeds about 20 km/sec the data in Figures 6, 7, and 8 suggests that use of Na D2 alone might yield cleaner filter bandpasses and higher peak transmissions. However, before any final choice could be made, additional MOF spectral scans should be obtained to confirm the differences shown in these Figures.

In order to exploit the properties of the MOF just described for stellar pulsation studies, we would propose to employ a two-cell version of the filter (see e.g., Cacciani and Rhodes, 1984; and Rhodes et al. 1984) to "chop" between the red-and blue-wing bandpasses of the filter. The transmission profile from such a two-cell MOF would be similar to that shown in Figure 9. Here the dashed curve represents the filter profile when only the "red" bandpass is transmitted, while the dotted curve shows the profile when only the "blue" bandpass is being transmitted.

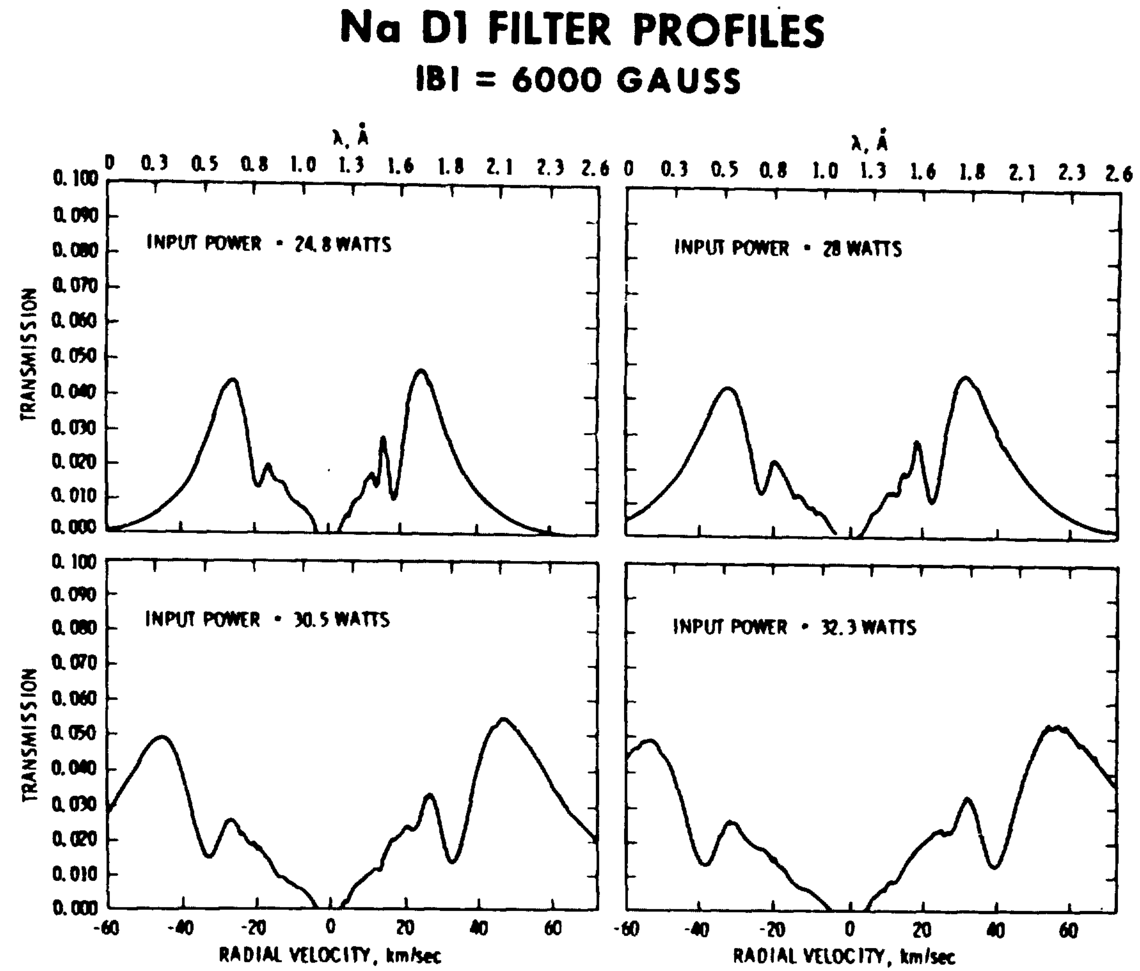

Figure 6: Same as Figure 5 but for four higher input power levels. The profiles are more complicated here because, at the higher optical depths generated by the higher input power levels, the transmission peaks due to several complete Faraday rotations appear in each wing.

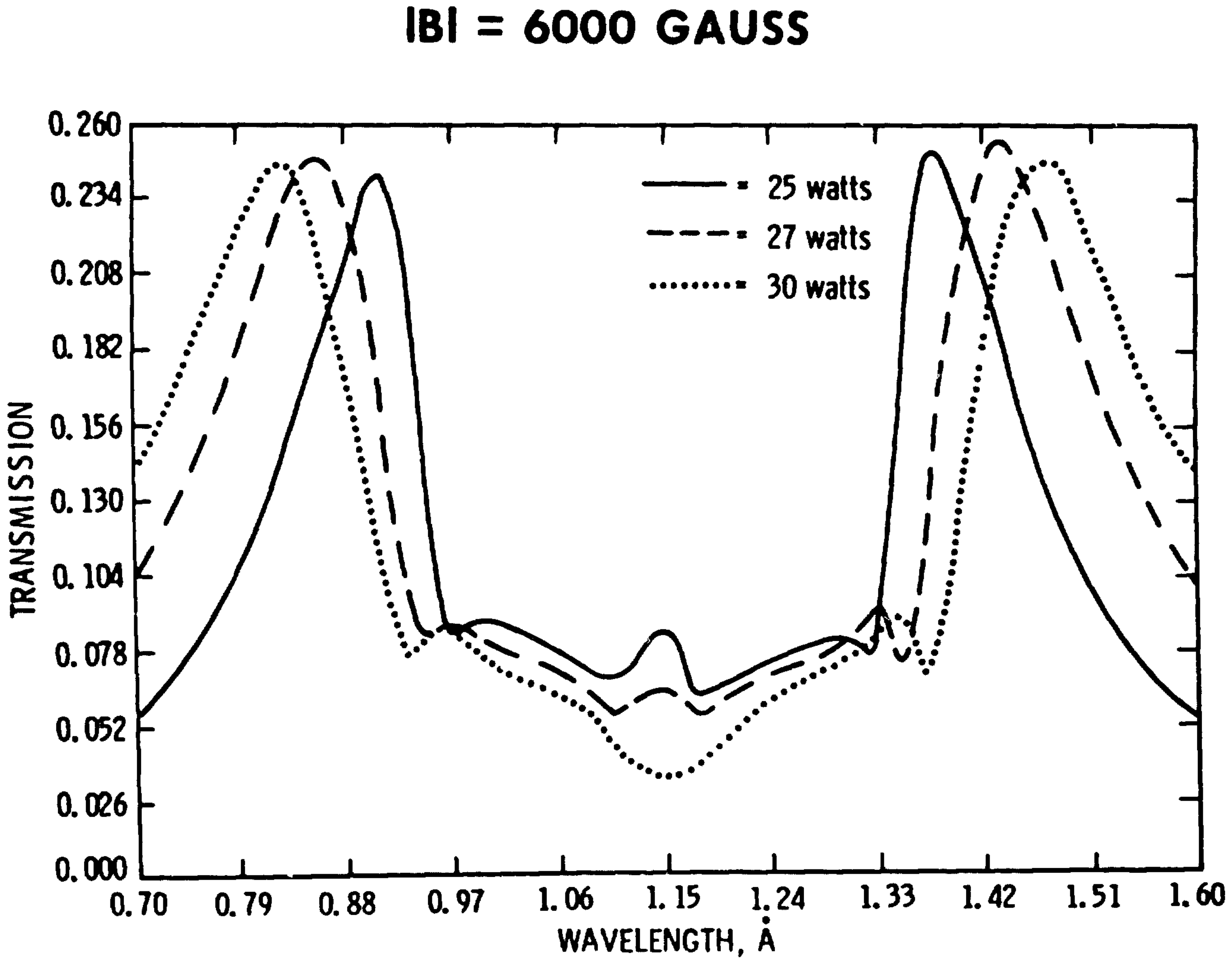

Figure 7: Same as Figure 6 except that the Na D2 line was employed instead of the D1 line as in Figures 5 and 6.

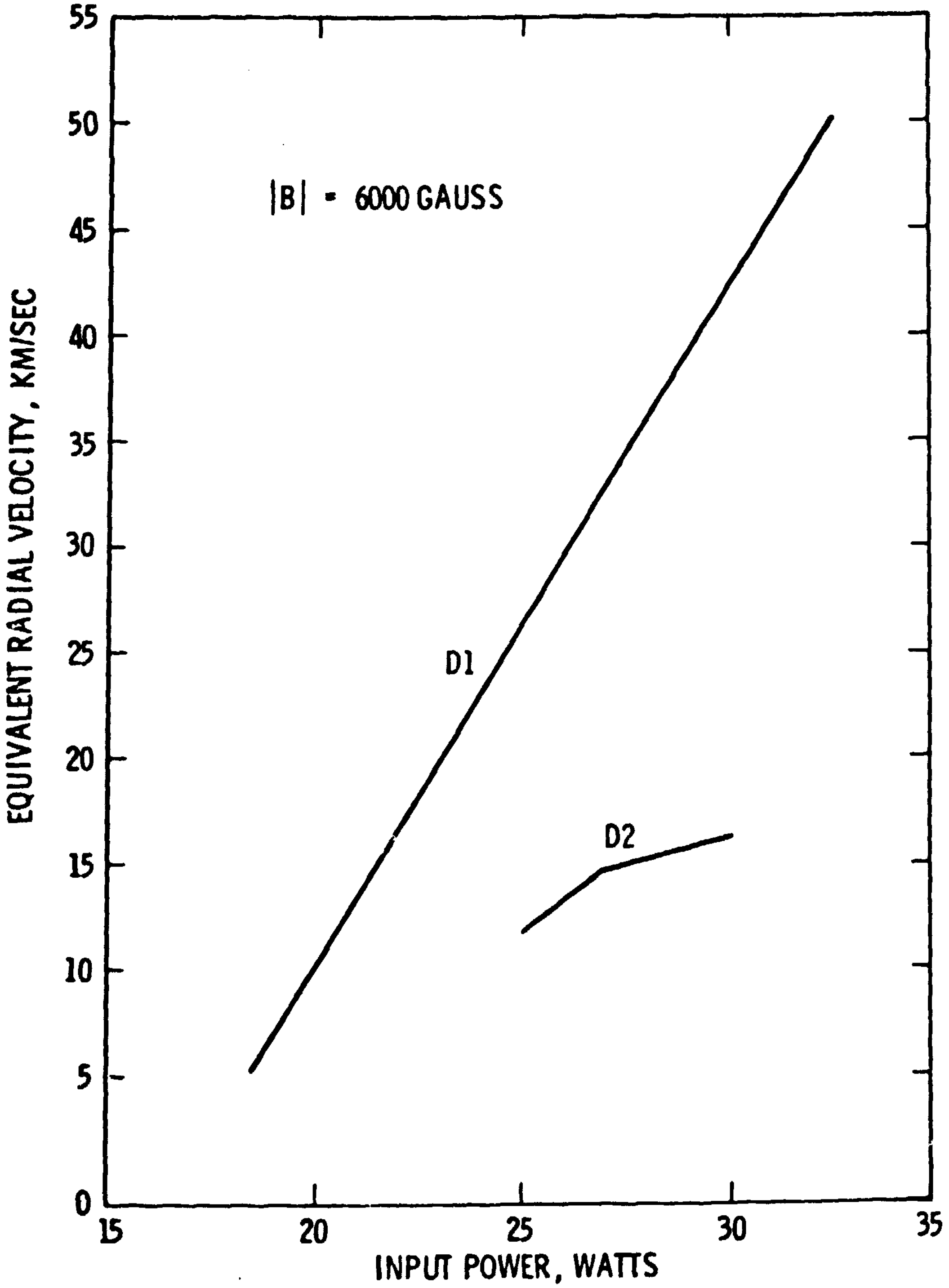

Figure 8: Same as Figure 2 except that the field strength is 6000 instead of 1000 Gauss. Large stellar radial velocity shifts could indeed be compensated for by adjusting the level of the input power each night and then stabilizing that power level for the duration of that night.

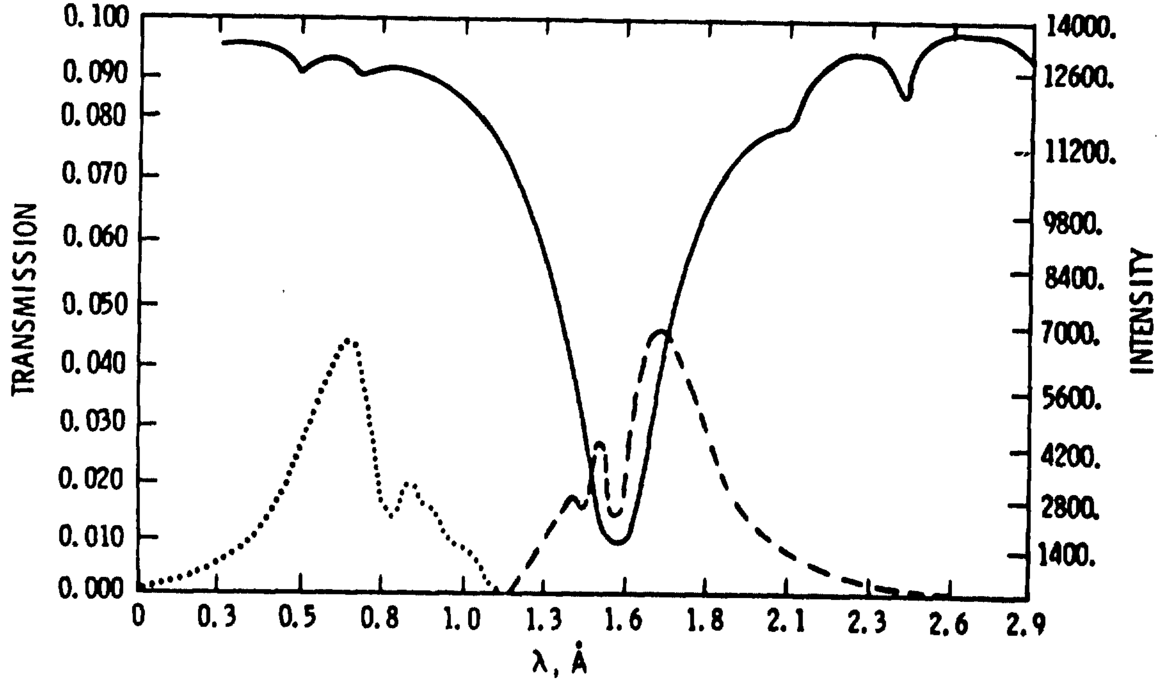
SOLAR AND FILTER PROFILES

Figure 9: The result of employing a two-cell filter rather than a one-cell filter is shown schematically. Here the dashed profile represents the transmission of the filter at one moment in time, while the dotted profile shows that only the other bandpass would be transmitted at a later moment. By electronically or mechanically tuning the two-cell filter, it is possible to "chop" sequentially between these two bandpasses. The solar D1 line profile is shown at the top for comparison. It has been shifted redward by 0.37A to simulate a stellar radial velocity of 19 km/sec.

Superimposed upon the MOF transmission profile scans is a red-shifted profile of the solar D1 line. Clearly, a two-cell filter system could chop between one side of the stellar line and the stellar continuum. By recording interspersed intensity time series with the filter alternating between the two bandpasses, we would be able to obtain one signal that is sensitive to the Doppler shift of the Na line and another signal that is a record of telluric atmospheric changes. By simply dividing the first of these two time series by the second, we would then be able to remove the telluric-induced intensity shifts recorded in the chosen bandpass to first order.

Returning once again to the ability of this proposed scheme to put together time series stretching over many days, we note that a slight alteration in the level of input power to the cells from one night to the next would allow us to keep the bandpass fixed with respect to the stellar line profile even though the star's radial velocity was apparently being changed by the earths orbital motion. A simple closed-loop servo system would be employed each night to keep the input power level steady throughout that night, and then the mean power level would be adjusted prior to the next evening's observing. Thus, the input power would make a series of discrete jumps but would be kept stable between each change.

3. MECHANICAL CHANGES REQUIRED

The relatively high power levels necessary to reach the largest wavelength shifts shown in Figure 8 mean that the MOF cells would have to be run at relatively high optical depths. Hence, unless, an alteration is made in the physical construction of the cells themselves, there is a reasonable chance that the end windows of the cells could become clouded in an unacceptably short interval of time. Therefore, we are proposing that the physical arrangement of the MOF cells be altered for the stellar case. Our proposed alterations are illustrated schematically in Figure 10. Hence we sketch the existing solar MOF design at the top and our proposed stellar design at the bottom. In the solar case the need to produce an image of the extended solar disk limits the length-to-diameter ratio of the cells. Thus, the existing metal pole pieces cannot become very long before the solar beam is partially obscured by the sides of the pole pieces.

Since the pole pieces are employed in part to keep the end windows relatively cool and to provide a place for the vapor in the cell to deposit before it reaches the end windows of the cell, it becomes important to move the end windows farther from the heated "pits" (i.e., the sources of the vapor) as the optical depth inside the cells is increased. Thus, with the high optical depths envision-

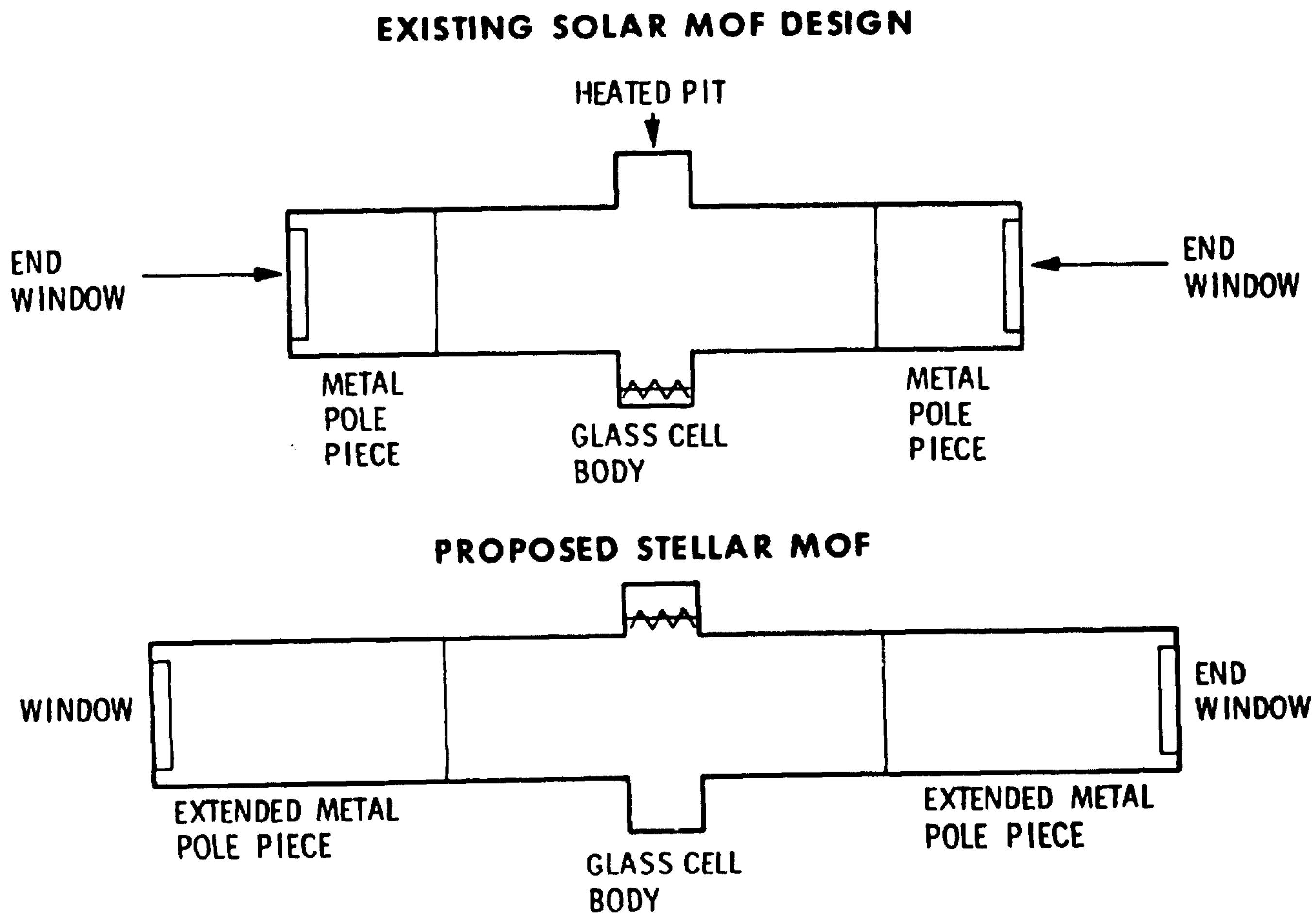

Figure 10: (top) Sketch of existing MOF cell design as is currently employed at Mt. Wilson for solar observations. (bottom) Proposed alteration in the cell design for the stellar application. The pole pieces would be longer in order to keep the end windows further away from the heated pits containing the Na.

ed for the stellar case, we are proposing that extended pole pieces be employed which would in fact move the end windows well away from the vapor sources. Since in the stellar case we would not be imaging an extended object like the sun, the larger length-to-diameter ratio of such a modified cell should not pose a problem.

We should also point out here that additional photons can be captured by observing the intensity in both Na D lines simultaneously, albeit at the expense of a more complicated filter profile. By simply removing the calcite plate which allows us to choose which of the two D lines we are using at any one moment, we can indeed employ both lines at the same time, as long as the prefilter we employ is at least 15 A wide. We have in fact employed this dual-line mode of operation in many of our measurements of solar oscillations during the past few years, and we believe that the confusion introduced by the more complex filter profiles should be offset by the added photons that would be available.

SUMMARY

We have outlined an alternative method of employing the magneto-optical filter for observations of stellar pulsations. The method we have described should allow an observer to observe a single star for more than a few nights each year and should also allow for the monitoring of the telluric atmospheric contamination to the stellar intensity time series. We have also indicated the modifications to the filter design which would be necessary to allow us to operate in this manner. Before we intend to try out the scheme we have described at a large telescope, we will first fabricate a few of the revised MOF cells and build the closed-loop servo system for the control of the input power. If laboratory tests with this hardware yield promising results, then we will attempt to test our ideas with actual stellar observations.

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