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OBSERVATIONAL EVIDENCE OF LINE SHIFTS INDUCED BY THE CONVECTIVE OVERSHOOT IN THE ATMOSPHERE OF RED GIANTS

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ABSTRACT

The spectra of four M giants have been observed in the infrared *K* band with the Fourier Transform Spectrometer at the Canada-France-Hawaii telescope. The frequencies at line bottom of the lines of Fe I, Ca I, and the first overtone band of CO are measured. Calibration with accurate laboratory frequencies make it possible to measure a blueshift of the high excitation energy lines of iron with respect to the low-energy lines of CO, in the range from 0 to 6 eV. In one of the stars a velocity gradient is also observed among the lines of CO. This differential blueshift is interpreted as being caused by the convective overshoot into the reversing layer. The observed blueshift appears to be 5–10 times larger than in the Sun, on average, although there are substantial variations from star to star.

Subject headings: convection — infrared: spectra — stars: atmospheres — stars: late-type

I. INTRODUCTION

Velocity differences between the first overtone lines of CO and the lines of neutral metals have been reported for some time in the atmosphere of late-type giants and supergiants such as α Boo, α Her, α Ori, and α Sco (Bopp and Edmonds 1970; Maillard 1974; Brooke, Lambert, and Barnes 1974). These differences were generally described as being caused by differential expansion of the different species in the upper atmosphere. This expansion was thought to be related to mass loss, but the calculated mass-loss rate was unacceptably high. The extension of the observations to the fundamental band of CO led to the detection in the same stars of multiple components of the CO lines (Bernat 1981), providing direct evidence that supergiants lose mass. On the other hand, for late-type stars of luminosity class III whose microwave spectrum does not show evidence of CO emission from a circumstellar envelope (Knapp and Morris 1985), the overtone bands of CO must be formed in the photospheric layer, and differences in line shifts between the CO and metallic lines should be due to photospheric phenomena.

Ridgway and Friel (1981) have detected an asymmetry in the CO lines of eight K- and M-type giants, by co-adding the bisectors from many lines of the $\Delta v = 2$ vibration-rotation band. By analogy with the bisector shapes measured from metallic lines in the Sun (Dravins, Lindegren, and Nordlund 1981), they concluded that convective motions are present in the atmosphere of these stars. The bisectors of the solar lines are now well interpreted in terms of the convective motions that cause the surface granulation revealed by high spatial resolution images of the solar disk. The hot rising granules give rise to a blueshifted component of the line profile, whereas the cooler falling material generates a component with the opposite shift. The combination of the area and brightness ratios between the granules and intergranular lanes leads to a net blueshift of the lines. A detailed simulation of this mechanism has been performed by Nordlund (1980, 1982), who was able to reconstruct the observed line profiles and shifts. Excellent reviews of the asymmetries and line shifts in photospheric spectra have been given by Dravins (1982, 1985), and Dravins and Lind (1984).

For stars other than the Sun, the observational evidence of convective motions is limited to the shifts and profiles of lines integrated over the entire stellar disk. The emphasis up to now has been put on the determination of the line bisectors in F, G, and K stars (Dravins, Lindegren, and Nordlund 1981; Gray 1982; Gray and Toner 1986). The precise determination of the line bisector requires spectra observed with very high resolution (10^5) and signal-to-noise ratio (500), and only unblended lines can be used. It has therefore been limited to very bright stars. The extension to M-type stars becomes only feasible in the infrared by using CO lines for which the blending of line profiles can be compensated by the large number of lines available (Ridgway and Friel 1981).

The results of Ridgway and Friel showed large variations in the bisectors of the M0.5, M3.3, and M4.3 stars they observed, but each type was represented by only one star. In order to estimate the importance of convection in the atmosphere of M-type giants, and the possible variations with time or the variations between stars of the same spectral type, it is necessary to obtain data on a significant sample of these stars. It appeared fruitful as a first step to look only at the differential line shifts, at line bottom, of a large number of lines of CO and metals. Fourier Transform Spectroscopy gives access to a broad spectral range with a uniform metrologic quality. This method of observing many lines simultaneously does not require an absolute velocity calibration of the stellar spectrum, and it is relatively insensitive to errors in the frequency or phase shift of the reference line. In FTS spectra, the accuracy on the position of the bottom of a line is proportional to the resolution and the signal-to-noise ratio (Maillard 1973) in such

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a way that for an unblended line observed with a limit of resolution of 3 km s^{-1} and a S/N ratio of 100, a relative velocity can be measured with an uncertainty of 0.03 km s^{-1}. Simple tests show that although the line asymmetry is much reduced by convolution with an instrumental profile with this lower resolution, the shift at line bottom is much less affected. In previous studies the lack of accurate laboratory measurements severely limited the usefulness of the measurement of differential line shifts. The recent availability of interferometric measurements for several molecules and metals of astrophysical interest makes it possible to reinvestigate the problem.

The goal of this project is to determine with precision the differential line shifts of metals and CO in near-infrared spectra of red giants. It has been shown that the line shifts caused by convective motions in the Sun could be described precisely as a function of the excitation energy and line depth (Nadeau 1988), and it should be possible to obtain a similar description for late-type stars. The project is aimed first at a homogeneous sample of early M giants that show little variability, in order to establish the accuracy of the method as well as the general properties of this group of stars and the variations from one star to the other.

In this paper we present evidence of the convective motion in four M giants (M0 to M3) obtained by the measurement of the relative shifts of lines of CO, Fe I, and Ca I, observed in the K band and covering a range of excitation energies from 0 to 6 eV. We also briefly discuss the directions in which improvements could be made to increase the accuracy of the measurements. The observations are described in § II, and the method of analysis is presented in § III, with a discussion of the accuracy of the line frequencies measured in the laboratory. The results are presented in § IV, and their interpretation in terms of convective motions is discussed in § V.

II. OBSERVATIONS

The observations were made at the Cassegrain focus of the 3.6 m Canada-France-Hawaii telescope, with the Fourier Transform Spectrometer described by Maillard and Michel (1982). The interferometer, equipped with a Si-coated ($\lambda/4$ at 1.6 μm) Infrasil beamsplitter, is used in ambient air. The InSb detectors are cooled to 55 K. The bandpass was limited by cold K-band filters. The seeing was on the order of 1″, and the diameter of the diaphragm on the sky was 8″, thus ensuring the stability of the signal.

A limited sample of four M III stars with K = 0.5–1.7 mag were selected in order to test the method of differential velocity measurements. A journal of the observations is presented in Table 1. The stars are identified by their number in the *Bright Star Catalogue* (Hoffleit and Jaschek 1982). The stars HR 8232 and HR 3982 were observed in order to measure the telluric absorption features.

TABLE 1

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Star	Type	Date	S/N Ratio	Bandpass (cm^{-1})	Spectral Resolution (cm^{-1})
HR 0045......	M2 III	1984 Oct 13	70	3775–5700	0.09
HR 1451......	M3 III	1984 Oct 13	38	3775–5700	0.09
HR 8232......	G0 Ib	1984 Oct 14	46	3775–5700	0.09
HR 3950......	M2 III	1985 Dec 21	72	3775–5700	0.08
HR 1866......	M0 III	1985 Dec 23	74	4000–5300	0.08
HR 3982.....	B7 V	1985 Dec 23	68	4000–5300	0.08

III. ANALYSIS

a) Line Detection and Identification

The first step of the analysis consists of making a list of the frequencies and central depths of all the lines detected in the stellar spectra. The noise level is measured at both ends of the spectra, outside the optical filter bandpass. A frequency measurement is made for every line showing a difference in intensity larger than 6 times the rms noise between its central depth and one of the two adjacent maxima. The precise position of the minimum is determined from a parabolic fit to the three points closest to it.

Many of the lines detected are contaminated by other stellar lines or by telluric lines. The following procedure is adopted in order to reduce the effect of contamination by the telluric lines: a list of the lines detected in the spectrum of an early-type comparison star is produced and whenever a line from this list is within 3 km s^{-1} of a line in the spectrum of the program star, this line is rejected. This procedure was found to be more efficient than taking the ratio of the spectra of the giant and comparison stars because it was not possible to observe bright comparison stars through the same atmospheric conditions as those of the program stars. From our experience of observing at Mauna Kea, we have determined that lines of different atmospheric constituents do not vary in the same way with time so that atmospheric absorption cannot be simply scaled as a function of air mass.

Because of the very high density of the lines in the spectrum, two lines can be superposed in such a way as to be detected as a single line. In order to avoid blended lines, the distribution of linewidths is plotted, and the lines in the tail of the distribution are eliminated. In addition, lines whose half-width at half-depth on the blue side is different from that on the red side by more than 20% are eliminated. Such an asymmetry is much greater than the asymmetries expected from convective motions (see, e.g., Ridgway and Friel 1981). A test of the inclusion of these asymmetric lines did not modify the results otherwise than by increasing the dispersion.

Each line detected in the spectrum of one of the program stars and selected according to the above criteria, is identified by comparing its frequency with lists of laboratory frequencies for CO, Fe I, Ca I, and Si I, which have strong absorption lines in the atmosphere of red giants. The frequencies of the stellar lines are corrected for the velocity of the star with respect to the observer. In a first analysis this velocity is obtained from Hoffleit and Jaschek (1982); the analysis is then repeated using the average velocity of the identified lines. In one case (HR 1451) it was necessary to repeat this procedure a few times, the catalog value being different from the final one by 2 km s^{-1}.

The identification of a stellar line with a laboratory one is based entirely on the agreement of their frequencies within an identification range chosen small enough to limit the noise from spurious identifications but large enough not to bias the results. It is obtained from the quadratic sum of the uncertainties on the frequencies of the stellar and the laboratory lines, to which is added linearly a velocity range of ± 1 km s^{-1}.

b) Frequency Calibration

The accuracy of the determination of the velocity as a function of energy and line depth by the comparison of lines from different chemical species will depend on (*a*) the internal accuracy of the frequency measurements in the stellar spectra, (*b*) the accuracy of the corresponding laboratory frequency determination for the different species both internally and with respect to each other, and (*c*) the accurate correction of the line shifts due to differences in pressure or isotopic composition between the gases observed in the stars and in the laboratory. Gas densities in the atmospheres of red giants being very low, observations of laboratory gases should be made at pressures low enough to render the pressure shifts negligible. Those three points have to be carefully checked.

The stella spectra are calibrated by recording the interference fringes in the light of a stabilized He-Ne laser (6328 Å). Its vacuum frequency is used for the reduction of the interferograms. To obtain the vacuum frequency of lines in the stellar spectra, it is necessary only to correct for the difference between the index of refraction of air at the frequency of the laser and at the frequencies of the stellar lines. The formula of Edlén (1966) is used with a pressure of 460 torr and a temperature of 0°C, corresponding to the average ambient conditions at the telescope. The variations in temperature and pressure, within the range of values observed at Mauna Kea, have a negligible effect on the difference between the indices of refraction of the laser and stellar lines. This ensures a very high internal consistency of the frequencies in the stellar spectra.

The laboratory frequencies for CO are obtained from the Dunham coefficients calculated by Guelachvili *et al.* (1983). For the low vibrational levels and for rotational levels up to $J \approx 60$, their calculation is based on many interferometric measurements from different kinds of sources, including one set of data calibrated with respect to the ^{86}Kr standard frequency and made at pressures of the order of 0.1 torr (Guelachvili 1979). The rms deviation of the observed frequencies with respect to the ones obtained from the coefficients is 15×10^{-6} cm^{-1}. Pollock *et al.* (1983) have measured by heterodyne techniques 11 lines of the 2–0 band using an absorption cell with an internal pressure of 0.15 torr. The estimated absolute accuracy of these data with respect to the cesium frequency standard is 5×10^{-6} cm^{-1}. Their measurements of the shifts of a few lines of the 2–0 band as a function of pressure showed these shifts to be on the order of 1×10^{-6} cm^{-1} at 0.15 torr. The frequencies of Guelachvili are found to be 0.00068 ± 0.00001 cm^{-1} higher than those of Pollock *et al.* The absolute uncertainty of the CO frequencies therefore should be less than 0.0007 cm^{-1} for rotational levels up to $J \approx 60$. For the rotational levels with $60 < J < 90$, the coefficients calculated by Guelachvili *et al.* are based on the data of Mantz and Maillard (1974), obtained from the observation of a flame at atmospheric pressure. These data have been calibrated with respect to low pressure measurements for low J values, and an upper limit of 3×10^{-4} cm^{-1} can be put on the pressure shifts. The transitions presented in this paper and having such high J values have an absolute uncertainty of 0.001 cm^{-1}.

The laboratory frequencies for Fe I are taken from the interferometric measurements of Biémont *et al.* (1985). These measurements are calibrated with respect to the infrared lines of Ar I whose frequencies were obtained by Norlén (1973) from interferometric measurements themselves calibrated with respect to the ^{86}Kr standard. The internal consistency of the Fe I and Ar I frequencies in the different spectra used by Biémont *et al.* is on the order of 5×10^{-9} times the frequency (Learner 1987), so that the internal consistency with respect to the krypton standard is equal to those of the system of Norlén, that is 0.0003 cm^{-1}.

The data of Biémont *et al.* were obtained with a hollow cathode containing 3 torr of argon gas. The internal accuracy of the Fe I data has been shown by Nadeau (1988), from a comparison with the solar spectrum, to depend on the multiplet considered, and to be generally better than 0.002 cm^{-1}. Corrections were applied to the frequencies of Biémont *et al.* according to these results. These corrections were never more than 0.0035 cm^{-1}, and their net effect was to reduce the blueshift of the iron lines. The remaining absolute uncertainty of the laboratory frequencies of the CO and Fe I lines presented in this paper is estimated to be of the order of 0.001 cm^{-1}.

The infrared spectrum of Ca I has been observed by Risberg (1968) with a grating spectrometer and a hollow cathode discharge tube as the source. The systematic instrumental uncertainty is larger for grating than for FTS spectrometers, and Risberg estimates the uncertainty of his measurements at 0.016 cm^{-1}. This large uncertainty precludes using the Ca I lines for the determination of differential velocities, but their relatively small scatter makes them useful for comparisons between stars.

IV. RESULTS

The velocity of the lines of CO, Ca I, and Fe I detected and selected according to the criteria outlined above, is plotted in Figure 1 as a function of the excitation energy. The lines of CO are represented by dots, the lines of Ca I by triangles, and the lines of Fe I by squares. The uncertainty of the calibration of the lines of CO and Fe I is small with respect to the observed velocity dispersion, but it is significant for the lines of Ca I, as mentioned above.

A difference in velocity is clearly apparent in Figure 1*a* between the CO lines and the Fe I lines of HR 0045. A velocity gradient with energy of the same magnitude is also apparent among the lines of CO. On the other hand the lines of Ca I are redshifted with respect to the iron lines by nearly the same velocity as the low energy lines of CO. The iron lines of HR 3950 and HR 1866 are also blueshifted with respect to their CO lines, as shown in Figures 1*c* and 1*d*; the shift is smaller, however, and there is no gradient apparent among the lines of CO. This smaller blueshift is correlated with a redshift of the lines of Ca I at 4.7 eV with respect to the lines of CO. The scatter in the velocity of the lines of HR 1451 is much larger than for the other stars, and this is certainly due in part to the fact that the signal-to-noise ratio of the spectrum of this star is only half that of the other stars. The lines of iron in particular suffer from a large dispersion; they are also generally weaker than the other lines. When considered together the lines of iron and calcium show a large blueshift with respect to the lines of CO.

As shown in Figure 2 there is a strong correlation between the line depth and the excitation energy for the lines of CO and Fe I. Although the data in Figure 1 have been plotted as a function of energy, the observed blueshift may be due in a large part to differences in line depth. Examination of the iron data does show some evidence of a dependence of the velocity on the line depth, but the present data are not sufficient to distinguish clearly the dependence on line depth from that on excitation energy.

The median of the velocity distributions is plotted in Figure 3 for the lines of CO and for the lines of Fe I. In order to look for evidence of a velocity difference between the high-energy and low-energy lines of CO, these lines have been separated into two more or less equally populated groups with an otherwise arbitrarily chosen border at 1 eV. In the case of HR 1451

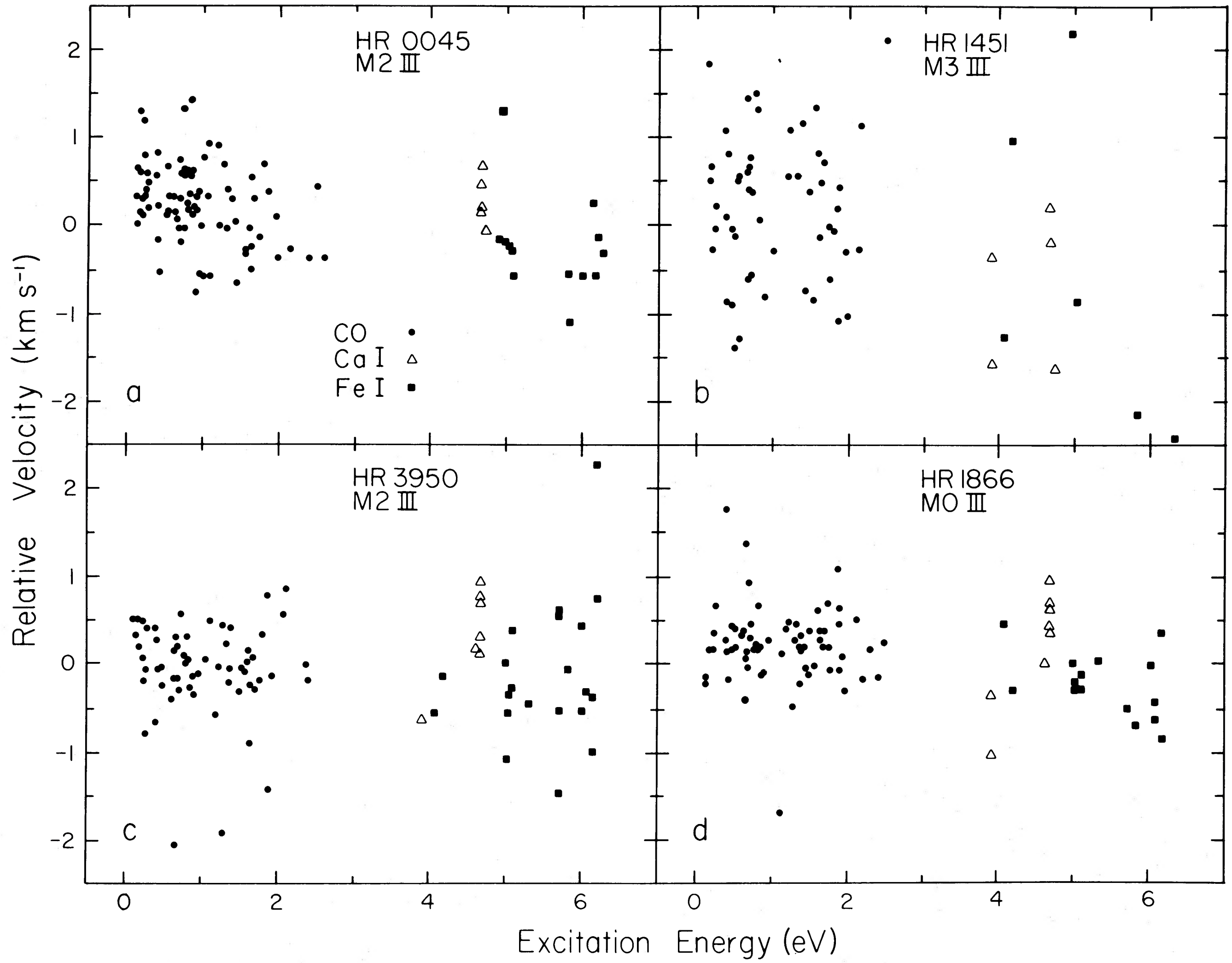

FIG. 1.—The relative velocity of the lines of CO, Ca I, and Fe I is plotted as a function of excitation energy. Each symbol represents a spectral line, the lines of CO being represented by dots, the lines of Ca I by triangles, and the lines of Fe I by squares.

the lines of calcium and iron have been combined together, but for the other stars the lines of calcium are not taken into account because the uncertainty in their calibration is large with respect to the dispersion of the lines of iron. The median of the distribution is plotted rather than the average, in order to reduce the effect of the contaminated lines.

Straight lines are fitted to the medians in Figure 3. A comparable slope for the Sun has been plotted from the velocities calculated for the lines of iron having a depth of 75% and 25% at 0.5 eV and 5.5 eV, respectively, as determined by Nadeau (1988). This combination of line depth and excitation energy is chosen to correspond to the low-energy lines of CO and the lines of Fe I, in the M giants.

As foreseen in Figure 1, the straight lines fitted to the data in Figure 3 all show a blueshift of the high excitation energy lines with respect to the low-energy ones. These blueshifts are much larger than the uncertainties on the calibration of the lines of CO and Fe I. In all cases the measured blueshifts are larger than in the Sun, by factors of 2–8.

V. DISCUSSION

The observed blueshift of the lines of Fe I with respect to those of CO varies from 0.4 to 1.5 km s^{-1}. The mass loss that would be implied by such velocities for gas of photospheric densities can be estimated approximately. From the models of M giants calculated by Tsuji (1978) we obtain a number density of 2×10^{14} cm^{-3} at an optical depth of $\tau = 0.1$ for a giant with an effective temperature of 3000 K. For a star with a radius of approximately 50 $R_{\odot}$, the mass loss implied by a velocity of 0.4 km s^{-1} would then be approximately 10^{45} particles s^{-1}, equivalent to 3×10^{-5} $M_{\odot}$ yr^{-1}. This is a few orders of magnitude larger than reasonable values for the mass loss expected from the red giants in our sample, for which circumstellar envelopes have not been detected. Therefore the observed velocities must be related to oscillatory or cyclic motions rather than mass loss. Global oscillations with successively outward and inward motions are an unlikely explanation since all four stars observed show evidence of a similar

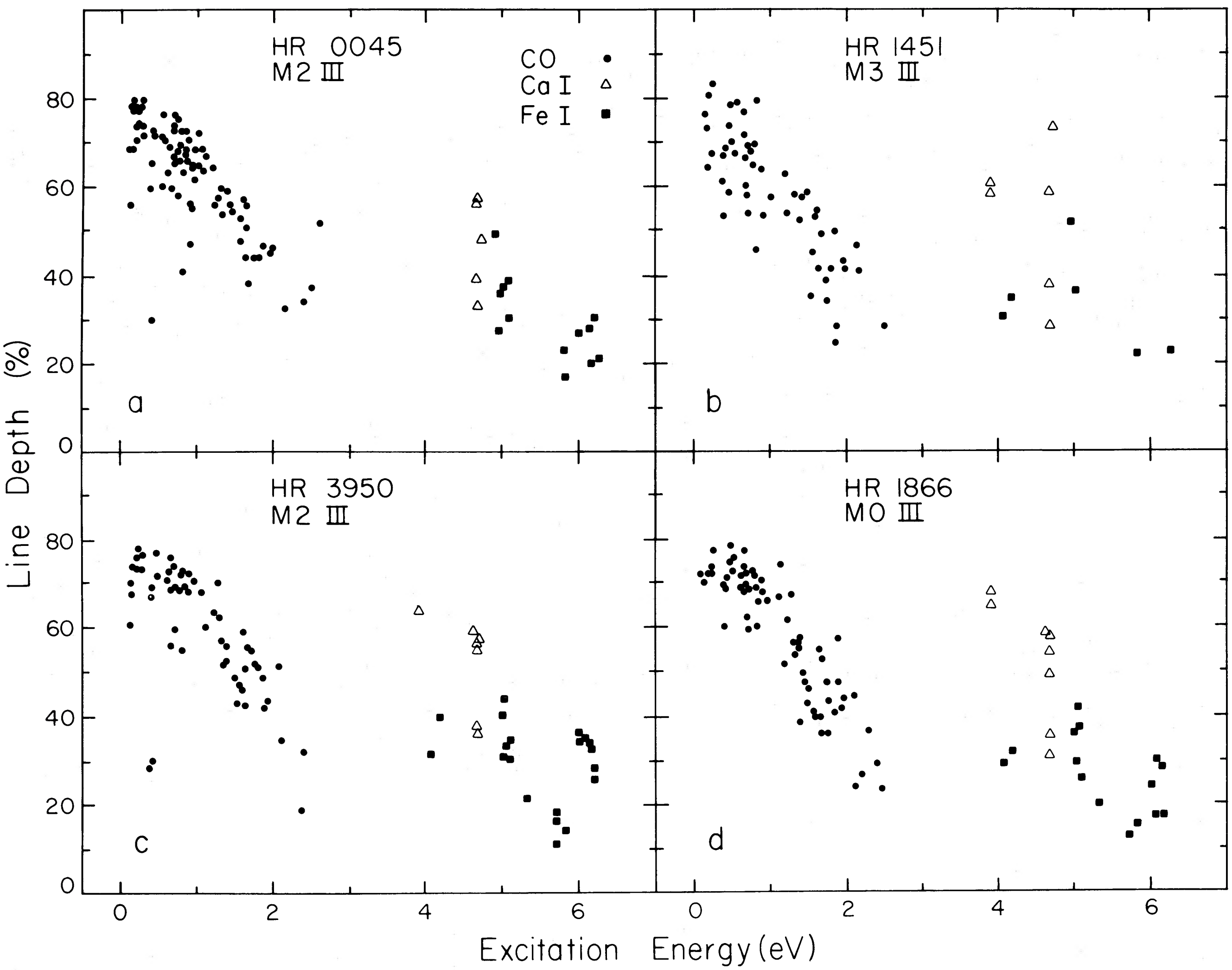

FIG. 2.—The central depth of the lines of CO, Ca I, and Fe I, expressed in percent of the local continuum, is plotted as a function of the excitation energy. The lines are identified as in Fig. 1.

blueshift of the lines of iron with respect to those of CO. The blueshift is probably due in part to both the higher excitation energy and the smaller depth of the lines of iron. An increasing blueshift at higher energy implies that negative velocities are correlated with hotter material. Convective overshoot into the reversing layer is the only mechanism that will cause such a correlation. This mechanism is also consistent with the possible dependence on line depth since the temperature and velocity differences between the upward and downward moving components are expected to decrease with height in the reversing layer so that stronger lines should show smaller blueshifts. It is therefore concluded that the relative blueshift observed in the M giants is produced by the convective overshoot in their atmosphere.

A physically significant comparison of the relative blueshifts in the Sun and the red giants requires that the differences in the observational procedures be taken into account. The observations of the Sun from which the line shifts have been measured were obtained at disk center (Delbouille, de Jager, and Roland 1973; Delbouille *et al.* 1981), while the observations of the red giants are limited to the measurement of quantities averaged over the whole disk. Since only the vertical component of the convective motions is correlated with temperature and brightness fluctuations and will produce line shifts, the projection of the vertical velocities on the line of sight implies smaller shifts near the limb and would lead by itself to a reduction of the integrated line shift to $\frac{2}{3}$ of the shift at disk center. The oblique penetration of the line of sight near the limb implies that the continuum and the absorption lines are formed in higher layers of the atmosphere, where the horizontal fluctuations in brightness, temperature, and velocity are less pronounced. This will result in a smaller shift of the lines formed at the limb, but also in a smaller contribution of the regions near the limb to the integrated line profiles due to limb darkening.

The line shift could decrease even faster toward the limb if there is a loss of the correlation between the brightness fluctuations of the continuum and the projection along the oblique line of sight of upward and downward moving components in the reversing layer. This could result from a penetration of the convective overshoot into the stable layers to heights that are of the order of the horizontal dimension of the convective cells. The calculations of Nordlund (1976) show the extent of the penetration in the atmosphere of the Sun to be on the order of 0.1 times the horizontal dimension of the granules, and that the

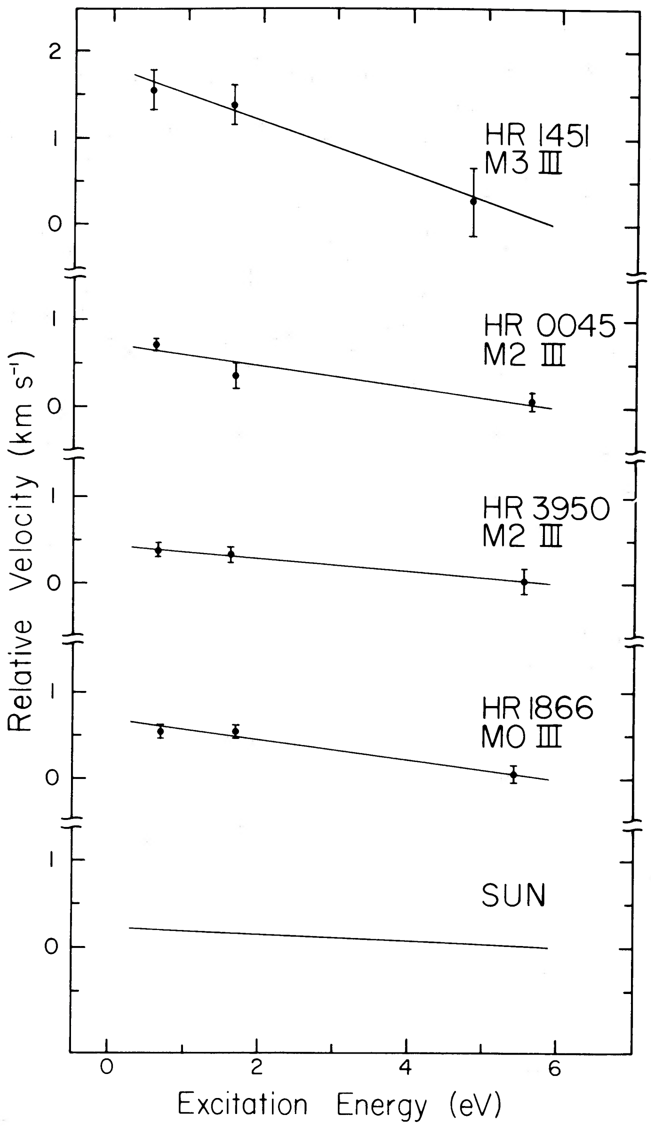

FIG. 3.—The median of the velocity distribution is plotted as a function of excitation energy for the lines of CO of energies below and above 1 eV, respectively, and for the lines of Fe I. In the case of HR 1451 the median at high energy corresponds to the distribution of both the Ca I and Fe I lines. A comparable slope for the Sun has been plotted from the velocity of the Fe I lines with a depth of 75% at 0.5 eV and 25% at 5.5 eV, respectively.

height of penetration depends essentially on the linear size of the horizontal fluctuations. Based on this argument we may assume a similar ratio of height to diameter in the red giants and that any loss of correlation between the brighter regions and the upward moving gas has only a small effect on the integrated line shifts.

The finite spectral resolution will also affect the shift measured at line bottom if the intrinsic line profile is asymmetric. The infrared line shifts in the Sun were measured from data with a spectral resolution of 0.015 cm^{-1} (Delbouille *et al.* 1981), while the spectral resolution of the observations of the red giants, as shown in Table 1, is coarser by a factor of 6. Numerical tests on simulated profiles show however that the limited spectral resolution of our data will have only a small effect on the line shifts although it will reduce the line asymmetries by a large factor. A similar test done by Dravins (1985) on solar lines confirms that the effect is small for a spectral resolution similar to that of the present observations.

Detailed modeling would be necessary to quantify the above considerations precisely. In the Sun, Dravins *et al.* (1981) show that the curvature of the bisectors of lines integrated over the whole disk is reduced by approximately a factor of 2 with respect to the curvature obtained at disk center. It would seem that a similar factor would be appropriate for the ratio of the shifts of the lines integrated over the disks of red giants with respect to the shifts that would be observed at disk center. The combination of this factor with the results presented in § IV would indicate that the difference in line shift between the strong low-energy lines and the weak high-energy lines is approximately 5–10 times larger in the M giants than in the Sun. This is in agreement with the conclusions of Ridgway and Friel (1981) and Gray (1982), from studies of line bisectors, that the blueshifts appear stronger in K and M giants than in the Sun.

This larger difference could be due to larger velocities in the upward and downward components, to a larger difference in temperature between the two components, or possibly to a larger relative area of the upward component. The height of penetration of the temperature and velocity differences certainly plays an important role. It is not possible however to discriminate between these factors with the present data. In order to determine the penetration of the horizontal temperature fluctuations it will be necessary to measure in particular the gradient as a function of line depth at high excitation energy. The blueshift of the high excitation energy lines with respect to the low-energy ones is caused by the higher temperature in the upward moving gas. If this blueshift is apparent also for lines of large depths, it would mean that the temperature fluctuations penetrate far into the reversing layer.

VI. SUMMARY

The main conclusions of this paper are as follows:

1. The infrared *K*-band spectra of four M giant stars show a blueshift of the high excitation energy lines of Fe I with respect to the low excitation energy lines of CO. For one of the stars there is some evidence that among the lines of CO those of higher excitation energy are blueshifted with respect to those of lower energy.
2. Because of the correlation between the line depth and excitation energy in the present data, it is not possible to separate the contributions of these two parameters to the blueshift.
3. Convective motion is the most likely cause of the observed line shifts. The observed dependence on excitation energy and/or line depth parallels that observed in the Sun.
4. When corrected for the difference in spatial and spectral resolution the line shifts observed in the spectra of the M giants appear to be 5–10 times larger than in the Sun, on average, although there are substantial variations from star to star.

This evidence of the convective motions in red giants was obtained with a relatively simple analysis. The data analysis has shown that the results can be improved by increasing the signal-to-noise ratio, and by developing methods to reduce the effects of contamination of the line profile. A broader coverage of the spectrum, in both the *H* and *K* bands, would make it possible to distinguish the dependence on line depth from the dependence on excitation energy: in the *H* band the lines of CO are weaker and the lines of Fe I stronger than in the *K* band. Increasing the star sample and monitoring a few stars for line shift variability would make it possible to determine the dependence on spectral type. Finally, the availability of accurate laboratory spectra of more atomic species is nearly as important as improved stellar data for the precise determination of the effects of convection in stellar atmospheres.

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