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The distribution of oxygen on the surface of ϵ UMa: an abundance distribution Doppler image

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Abstract. An excellent Doppler image of the surface of ϵ UMa shows a strong, sharply defined belt at the magnetic equator with oxygen abundance five orders of magnitude greater than the abundance in the magnetic polar regions. The centre of abundance-symmetry for oxygen is located quite precisely at latitude +28° and longitude 349°. A secondary belt of oxygen abundance is observed tilted at 60° to 70° to the primary belt. In this secondary belt the abundance is only enhanced about two orders of magnitude above that of the surrounding abundance plateau in the polar regions. The relative depletion of Cr by about three orders of magnitude in a belt around the magnetic equator is confirmed. It is noted that, qualitatively, the location of the primary belt of oxygen enhancement, its extreme abundance difference compared to the polar plateau and the existence of the secondary oxygen belt, might suggest a chemically separated wind as a likely mechanism for producing the oxygen abundance pattern even though the radiative forces should not be sufficient to selectively expel oxygen in a wind.

Key words: stars: chemically peculiar – stars: abundances – surface distribution – stars: Doppler imaging – oxygen – stars: individual: ϵ UMa – peculiar A

1. Introduction

ϵ Ursa Majoris (HD 112185) is the brightest of the Ap stars and among the best known. Its variable spectral line profiles were described by Struve & Hiltner (1943) but, in spite of being brighter than α^2 CVn, until recently ϵ UMa was much less studied for perhaps several reasons. Its line profile variations for elements such as iron and chromium were less pronounced than those of α^2 CVn, the rare earth lines were far less evident and, until late in the 1980s, the magnetic field was not reliably measurable and was known to be less than about 110 Gauss (Borra & Landstreet 1980) which is very small for an Ap star. While ϵ UMa may have less dramatic spectroscopic variations and a weak magnetic field, it is noteworthy because it appears more evolved than most Ap stars. It has a radius about 4 times solar (see Wehlau et al. 1982) instead of the expected value for an average main-sequence A0 star of about 2.5 times solar.

With the advent of Doppler imaging (Goncharski et al. 1982), it was evident that ϵ UMa was an ideal candidate for pioneering work because it had a reasonable value of V sin(i) of about 34 km.s^{-1} and it had such a weak magnetic field that very little Zeeman effect would be evident in the local line profiles. Furthermore, it is so bright that high resolution spectroscopy could be accomplished with short exposure times. As a result, the star has been the subject of several papers since 1980. Wehlau et al. (1982), Rice & Wehlau (1990), Donati (1990), Rice & Wehlau (1991), and Hatzes (1991) all dealt with some form of Doppler image of the surface of ϵ UMa. Most of these articles identified some symmetry in the distribution of iron and chromium on the surface of the star. Rice & Wehlau (1990) produced surface maps of the distribution of iron and chromium for both ϵ UMa and θ Aur. The maps of the surface of each star were interpreted in terms of ring features about an axis of symmetry where the axis is presumed to represent the magnetic axis of the star. For ϵ UMa, the iron and chromium had an apparent ring of maximum local line strength that was 50° in radius and centred on a position which (when converted to the standard ephemeris of Provin 1953) is at latitude +45° and longitude about 328° . The pattern of minimum abundance included a rough ring of radius 90° about the same location and so amounted to a minimum near the presumed magnetic equator. In his PhD thesis, Donati (1990) presents a map of the iron distribution with a strong spot slightly above the rotational equator at about longitude 340° with satellite spots at the same latitude on either side.

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** It is with great sadness that we note here the passing of Bill Wehlau in 1995. Bill began this work with us but missed the enjoyment of seeing the results.

Opposite this feature on the star's surface he finds a somewhat annular feature centred slightly below the rotational equator. Hatzes (1991) mapped chromium and concentrated on the region of relative depletion rather than enhancement. This was, as it turned out, a very successful strategy. He found a stronge relative depletion of chromium in a ring that would represent the magnetic equator of a symmetric field with positive pole at about latitude +15° and longitude (again converting to the ephemeris of Provin) of about 340°. A short paper by Rice & Wehlau (1991) on mapping in actual abundance values listed the range in variation over the surface of ϵ UMa for the abundances of iron and chromium. Each element was found to vary by about 2.5 dex from minimum to maximum surface abundance.

While the magnetic field of ϵ UMa remained essentially unknown for most of the work discussed in the previous paragraph, renewed efforts to detect the field and define the location of the magnetic poles was undertaken as the maps were being completed. Donati et al. (1990), using an FeII line to measure the field strength, determined that if the inclination is 65°, the positive magnetic pole should be inclined 74±6° to the rotational pole (equivalent to a latitude of +16°) and should be at a longitude of 345°. While the measurement of magnetic field using the lines of an element that is not uniformly distributed over the surface of the star can be criticized as being biased because of the non-uniform weighting different locations on the surface have in contributing to the total Zeeman effect measured, Donati et al. believe their observation is little affected by this problem. Bohlender & Landstreet (1990) have measured the field of ϵ UMa using the Hβ line, so that they are avoiding the surface bias problem. They determined a maximum in the effective field of 128 G and a minimum of -64 G and conservatively estimate the rotational latitude of the positive pole as being between 22° and 62° at a longitude of 339° for an assumed inclination in the range of 50° to 80°. For an inclination of about 55° the latitude of the positive pole would be about 25° with fairly generous limits.

The publication by Gonzalez & Artru (1994) of observations of the OI triplet at 7775 Å in several Ap stars showed that these lines exhibit very dramatic line profile variations and that they would give excellent maps of the surface abundance of oxygen. Gonzalez & Artru interpreted the line profile variations for ϵ UMa in terms of a belt of very enhanced abundance about the presumed magnetic equator of ϵ UMa and their interpretation was undoubtedly correct but it was clear that, with the excellent Doppler imaging possible, a very good map of the distribution could be obtained to complement what was less well known about the iron and chromium abundance. In particular, it was evident that the location of the axis of symmetry could be pinned down with vastly improved accuracy. We undertook to make observations of ϵ UMa in May of 1994 at the Dominion Astrophysical Observatory and we subsequently learned that Babel, Donati and Gonzalez had also undertaken observations. A preliminary report of the maps of Babel et al. (1995) is available and they do indeed see the expected belt of oxygen abundance. They also show that Ca is concentrated in a belt around the presumed magnetic equator. Since it was a poster paper, their opportunity to include discussion was limited but we shall make what comparisons we can between their work and ours in the discussion section of this paper.

Table 1. Spectroscopic observation log

HJD (244+)	phase decimal	phase (°)	λ_c (Å)	exp. time (min)	S/N
9477.7167	0.818	294	7775	30	222
9477,9146	0.857	308	7775	30	293
9478.7069	0.013	005	7775	30	555
9478.8354	0.038	014	7775	30	415
9478.8569	0.042	015	7775	30	586
9478.9902	0.068	025	7775	27	500
9479.6874	0.205	074	7775	30	256
9479.8124	0.230	083	7775	31	475
9479.9263	0.252	091	7775	30	344
9480.6873	0.402	145	7775	31	243
9480.8103	0.426	153	7775	30	525
9480.9179	0.447	161	7775	30	322
9481.6908	0.599	216	7775	30	624
9481.8109	0.623	224	7775	30	323

2. Observations and data reduction

The observations of ϵ UMa were taken with the coudé spectrograph of the 1.2m telescope at the Dominion Astrophysical Observatory. The camera used was the 9681 camera with a resolution of 55,000 and a reciprocal dispersion of 5 Å.mm^{-1} at 7770Å. The Reticon spectra of ϵ UMa were reduced using the RET72 and REDUCE programs described in Hill & Fisher (1986). All of the following reduction software is described in this reference.

First, the raw spectrum data files were processed with RET72 to apply gain corrections (for the four video readout lines), to apply flat–field division, and to associate arc spectrum files with the appropriate stellar spectra. The resulting arc and stellar spectra were stored in FITS format.

REDUCE was then used to generate spectra with heliocentric wavelength scales, by measuring line positions on the two arc spectra associated with each stellar spectrum (VELMEAS). Continuum rectification and resampling in wavelength were also done using REDUCE. The spectra were linearized with wavelength intervals appropriate to the spectral region. Once the rectified and linearized spectra were generated, they were converted to ASCII form so that individual line profiles could be extracted for input into the Doppler imaging programs.

Since an observed stellar line profile is in fact the convolution of the intrinsic stellar and instrumental profiles, the latter must be removed to eliminate any systematic error in the Doppler images due to artificial broadening. The deconvolution of the intrinsic stellar and instrumental profiles was readily achieved using the optimal filter method discussed by Brault & White (1971). The deconvolution program processed each observed stellar profile, and generated an input file of intrinsic

Table 2. Adopted parameters for ϵ UMa

Parameter	Adopted Value
T_{eff}	9500 K
$\log g$	3.5
$v \sin i$	33.5 $\mathrm{km\,s^{-1}}$
Inclination i	55°
Rotation period	5.0887 days
Micro turbulence ξ	1.0 $\mathrm{km\,s^{-1}}$
Macro turbulence	0.0 $\mathrm{km\,s^{-1}}$
Radius	4.3 solar

stellar line profiles for the Doppler imaging program MAPPER3.

Heliocentric Julian dates (HJDs) and radial velocity corrections were computed from the observation times and stellar coordinates using the VSUN program. The HJDs, exposure times, and central wavelengths of each spectrum are given in Table 1. The exposure times were usually 30 minutes in the OI 7770 Å region and 20 minutes in the other wavelength regions to minimize any phase smearing. Rotation phases for ϵ UMa were computed according to the ephemeris of Provin (1953):

$$HJD = 2434131.124 + 5.0887 \times E. \quad (1)$$

3. The parameters for the Doppler images

All maps in this paper were generated with the Doppler-imaging code of Rice et al. (1989). Here we use a modified version of the original code, partially described by Piskunov & Rice (1993). The code requires a model atmosphere from which it generates a grid of local line profiles. The local profiles are calculated for the element being mapped for all possible log abundance values of that element that might be encountered on the stellar surface (for oxygen this was -9.0 to -0.5 in steps of 0.1 Dex). For each possible abundance value, the calculation is done for twenty different line-of-sight angles. The atmosphere used in this case was a refined version of a model distributed by Kurucz on CDROM and was for T_{eff} of 9500 k, ten times solar metallicity and log(g) of 3.5. These values of T_{eff} and log(g) are consistent with the slightly post main-sequence stage of ϵ UMa. These values are the same as used by Babel et al. (1995). The adopted values for parameters such as microturbulence, $V\sin(i)$ etc. are given in Table 2. The values to be adopted for $V\sin(i)$ and i have been extensively discussed elsewhere (Wehlau et al. 1982, Rice & Wehlau 1990, Donati 1990 and Hatzes 1991) and there is little variation in the adopted values. Here we have simply chosen commonly used values, without further review. The images produced vary but little for $V\sin(i)$ and i values that fall within the small range adopted by the authors listed above.

The three oxygen lines of the triplet used for this mapping are 7771.944Å, 7774.166Å and 7775.388Å with log(gf) values respectively of 0.324, 0.174 and -0.046.

Doppler imaging requires good phase coverage of the full rotational cycle of the star if the image is to be equally reliable around the full sphere of the star. Substantial gaps in phase coverage will cause loss of information in the image about the longitudes corresponding to the poor phase coverage. Our phase coverage is fairly complete with a worse case separation in phase of 0.195 for the 7770Å region which encompasses the oxygen lines (see Table 1). The daytime gaps of 0.14 to 0.195 are larger than we would like, but this generally represents quite good phase coverage for our purposes.

For comparison purposes, it was thought useful that we redo a map of Cr for ϵ UMa using the data used in Rice & Wehlau (1990) but using newer imaging code. One reason for doing this is to allow a better comparison with the oxygen maps since the earlier maps by Hatzes (1991) and also by Rice & Wehlau (1990) do not use the ephemeris of Provin. Further, the maps found with the older code were presented with an emphasis on the locations of the regions of abundance maximum with large areas of low abundance simply displayed without contrast. Hatzes (1991) has shown that a much more significant image appears if the emphasis is on the areas of weak line strength. In his paper he shows that there is a clear region of lower relative Cr line strength about the magnetic equator for this (and two other) stars.

4. The Doppler images

4.1. The oxygen image

A sharply defined belt of excess oxygen is distributed about the presumed magnetic equator. The location of the pole of the axis of symmetry for the oxygen distribution can be established by choosing a location such that the oxygen distribution, as plotted along various great circles through the pole, all give a peak of abundance at 90° from the pole (see fig. 5 and fig. 6 for examples). If the symmetry defined by this belt does indicate the magnetic equator, the positive magnetic pole is within 2 or 3 degrees of longitude 349° and latitude +28°.

A weaker feature is seen running roughly along the meridian of longitude at about 10° (it is most prominent in the illustration of Fig. 1 at phase 0°). This is extended on the other side of the star by an apparent continuation along a great circle, seen south of the main belt and running along a meridian at about 190° longitude. This combination of two features might form a slightly irregular and broken great circle inclined to the main belt of oxygen enhancement. The axis of symmetry of this weaker belt would be at about longitude 280° and latitude about 0°.

Fig. 5 and Fig. 6 show plots of oxygen abundance along great circles that pass through the presumed positive magnetic pole. In Fig. 5 there is a plot of abundance variation along a great circle that passes through the magnetic pole at an angle of 90° to the line joining the magnetic and rotational poles. The dotted line represents the segment of the line that is toward larger longitudes (i.e. to the left from the magnetic pole as seen in the image identified as phase=0 in Fig. 1). The peak seen at 20° distance from the pole is caused by the weaker belt-like feature described above. The abundance of oxygen in this weaker belt feature is three orders of magnitude less than the abundance in the adjacent

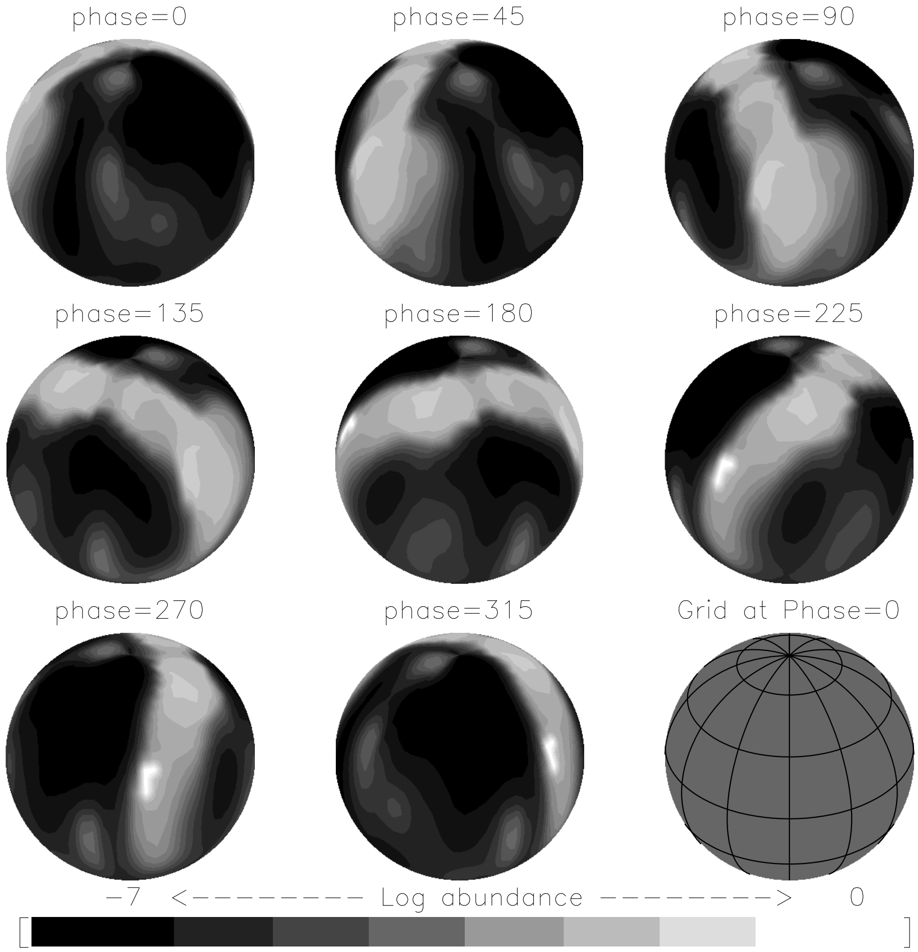

Fig. 1. Doppler image of the distribution of oxygen over the surface of ϵ UMa as mapped from the OI triplet at 7775Å. The inclination of the rotational axis is shown as 55°.

portion of the main belt of oxygen abundance along the magnetic equator but still well over an order of magnitude greater than the abundance in the surrounding depleted region near the magnetic positive pole. Here we see clearly depicted the very abrupt rise of abundance from the highly depleted values of abundance for oxygen around the magnetic polar region ([O/H] about -7) to the large abundances in the narrow band at the presumed magnetic equator ([O/H] about -3 to -2).

For those skeptical of the effectiveness of Doppler imaging who would like to see the concrete evidence for the weaker "belt" like feature in the original spectra so that they can confirm what the program is responding to, concentrate on phases 004° and 013° in Fig. 2. The absorption features caused by this weaker "belt" are marked for the lines of the oxygen triplet by arrows in the figure just under the spectrum for each phase. The depressions are less distinct for the spectra at phase 015°. The feature being tracked by the program and mapped south of the main belt along longitude 190° is only briefly in view and not clearly identifiable against the background of the main belt.

4.2. The chromium image

There is a clear resemblance beween the map of the chromium abundance (Fig. 3) on ϵ UMa and the map of Hatzes (1991). In comparing this map with that of Hatzes, note must be made of the difference in the ephemeris used in the two papers and that the plotting here is in terms of abundance rather than line strength. With the ephemeris of Provin (1953) used here, the phase comparison is such that (roughly) phase 0° shown in Fig.3 here corresponds to the image shown by Hatzes at phase 45° in his Plate 1. The illustration shown in Fig. 3 here as at phase 45° corresponds to Hatzes' illustration in Plate 1 at phase 90° etc.

In both the maps of Hatzes and the maps shown here for Cr, it would appear that the Cr does not increase steadily in abundance from the magnetic equator to the pole but instead seems to be most abundant in spots at intermediate magnetic latitudes. Since there is some correlation between the spots of enhancement seen here and those of Hatzes, this effect would appear to be real but perhaps further confirmation is in order before much thought is applied as to why there might be such an effect.

4.3. Image summary

Generally it would appear that:

1) There is a primary belt of oxygen enhancement concentrated sharply about the magnetic equator if the positive mag-

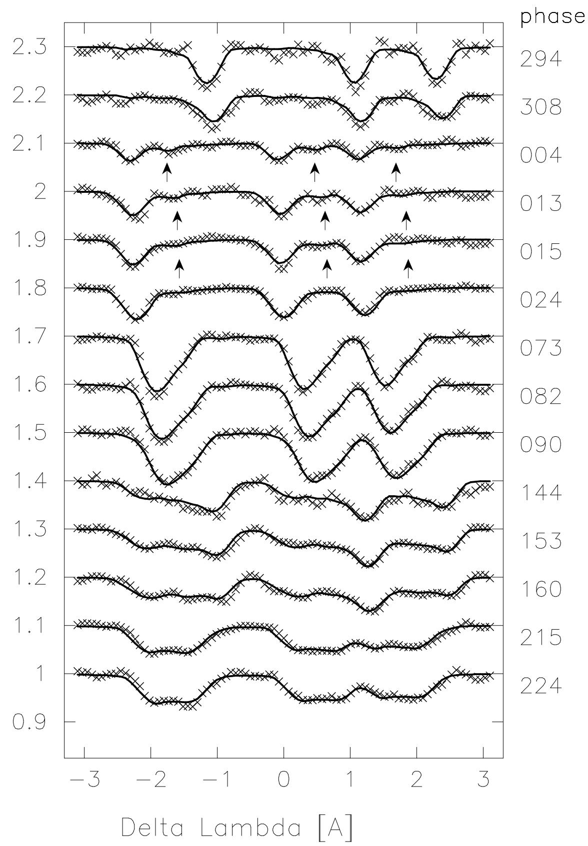

Fig. 2. Observations of the OI triplet taken at the phases shown on the right with the normallized depth scale on the left and the wavelength in Å shown on the horizontal axis. The horizontal scale is centred on 7773.55Å. The points labelled with an x are the data and the dashed line represents the fit of the Doppler image of Fig. 1 to the observations. The arrows represent the location for the spectral features that correspond to the "weak belt" in the image of Fig. 1

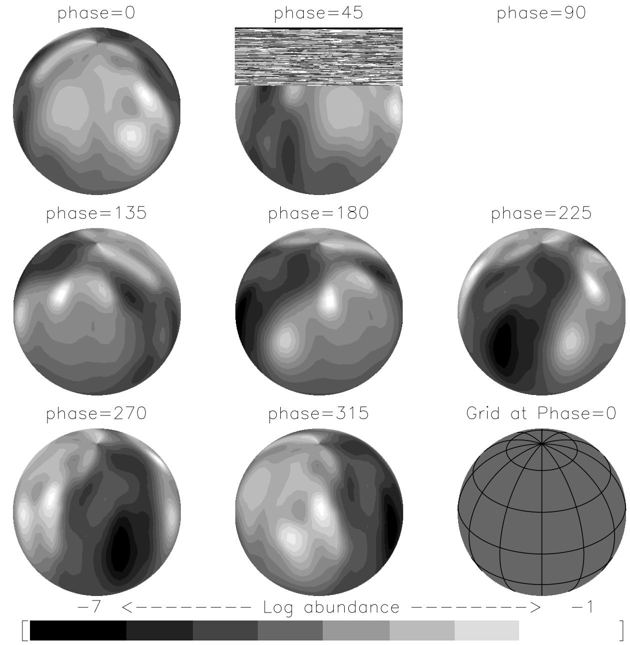

Fig. 3. The Doppler image of the distribution of Cr over the surface of ϵ UMa as mapped from the single Cr II line at 4558Å. The data for this map are from earlier observations (Rice & Wehlau 1990).

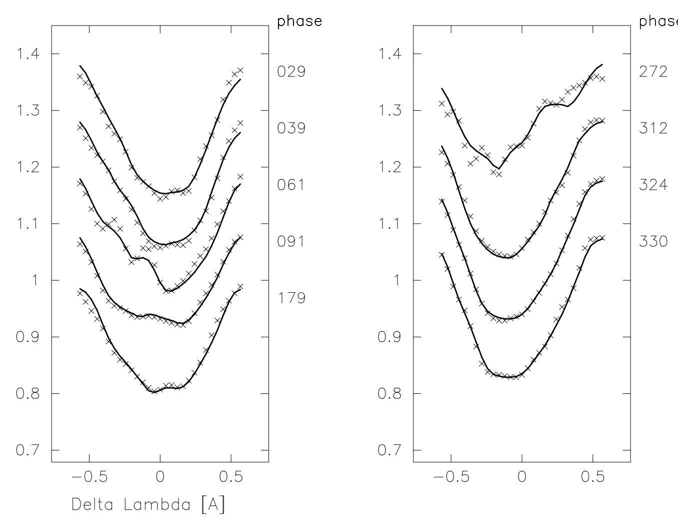

Fig. 4. The observations of the Cr II line at 4558Å are shown as x's and the dashed line is the fit to the data that corresponds to the map of Fig. 3. The data here are from Rice & Wehlau (1990).

netic pole is within about 3 degrees of latitude +28° and longitude 349°. This location for the positive pole is consistent with the observations of Bohlender & Landstreet (1990).

2) A weaker, slightly broken belt of lesser oxygen enhancement seems to lie along a great circle with the pole of the great circle at roughly longitude 280° and latitude 0°.

3) A clear belt of relative chromium deficiency that was first identified by Hatzes is confirmed to exist along the magnetic equator.

5. Discussion

There are a number of mechanisms thought to affect the abundances and abundance distributions on the surfaces of Ap stars. Diffusion (either radiatively driven or ambipolar) is widely accepted as the likely mechanism for producing the general abundance anomalies in the line forming layers of Ap star atmospheres. Horizontal variations in the abundances of elements on stellar surfaces might arise from several possible mechanisms and these different processes have varying effectiveness that can be characterized by the length of time it would take to build up a significantly spotted surface. The reader is referred to reviews by Michaud (1993) or Michaud (1996). Following Michaud (1996) we would identify the mechanism of selective mass loss, in the sense of a chemically separated stellar wind, as very effective. If active, the differentiated wind could create large depletion of metals near the magnetic poles on time scales of $10^4 - 10^5$ years (Michaud 1996). Acting on longer time scales than a differentiated wind would be magnetic field guiding of the subphotospheric and photospheric radiatively driven diffusion mechanism by either directing ions along the field lines or by the field creating a component of the radiative acceleration which is horizontal and which is directed along the surface away from areas where the field lines are horizontal. Since the horizontal component of the radiative acceleration is the more effective of these two mechanisms, we would generally look for enhancements of abundance to be around the magnetic pole as a result of the horizontal accelerations. The time scale for spot generation from these modifications of the diffusion effect is three orders of magnitude longer than for the selective mass loss mechanism. Zeeman desaturation of line absorption also strengthens the upward radiative accelerations where there is a horizontal field component. Thus the radiatively driven diffusion process at the subphotospheric and low photospheric level that produces the excess abundances in the Ap stars may, over time scales several orders of magnitude greater than a differentiated wind, produce abundance excesses near the magnetic equators of Ap stars. All of these mechanisms are discussed in Babel & Michaud (1991a). To the extent that ambipolar diffusion is playing a role in generating the observed abundance enhancements in Ap stars, it would tend to be suppressed as a mechanism in the presence of strong horizontal magnetic fields of the order of 1 - 10kG (see Babel & Michaud 1991b).

It is evident that the geometry of the magnetic field of a star is critical to understanding the mechanism that might be generating the horizontal abundance patterns on its surface. In the case of ϵ UMa, the field is very weak compared to other Ap stars and the data on the variation of the effective field from Bohlender & Landstreet (1990) are not sufficient to allow us to define the geometry, but the evidence doesn't suggest that the global field departs greatly from a dipole. The assumption of a primarily dipole geometry must, until better evidence is available, be taken on faith so that some speculation can begin on the mechanisms at work on this star.

5.1. The oxygen distribution

If the global field on ϵ UMa is essentially dipole, then the oxygen abundance is sharply confined to the region of horizontal magnetic field near the magnetic equator and is four or five orders of magnitude above the abundance plateau in the polar regions. It would seem from a review of possible mechanisms given above that, even with the relatively great age of ϵ UMa, the only mechanism that might produce such a dramatic abundance enhancement where the magnetic field lines are horizontal would be the chemically differentiated wind. Babel (private communication) and Gonzalez et al. (1995) have calculated, that the radiative acceleration on oxygen is much smaller than that for Cr and Fe and so it is very unlikely that oxygen could be expelled by radiative forces. The observation of the secondary belt of oxygen enhancement at longitudes greater than those of the magnetic poles by 10° to 40° may be very significant. This secondary belt is not evident in the image of Babel et al. (1995) but the appearence of this secondary belt, as emphasized above, is not a minor artifact of the imaging software. The absorption

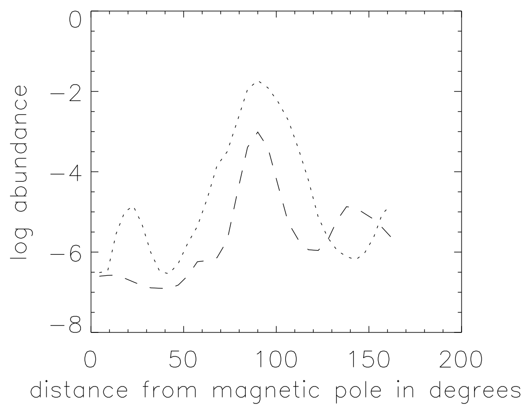

Fig. 5. A plot of oxygen abundance along a great circle through the positive magnetic pole. The great circle chosen for this figure is the one that is perpendicular to the meridian of longitude running through the magnetic pole. The line shown as dots represents the plot of [O/H] along the great circle in the direction of increasing longitude which is toward the left as represented in the image denoted as phase=0 in Fig. 1. The dashed line represents the plot of abundance along the same great circle but in the direction toward decreasing longitude which is toward the right as represented in the phase=0 image of Fig. 1.

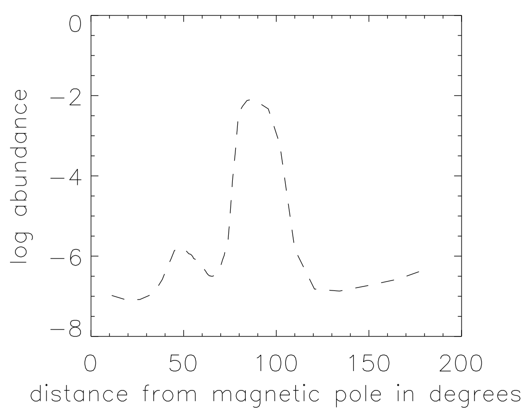

Fig. 6. Another plot as in Fig. 5 but here the [O/H] abundance is plotted for a narrow strip along a great circle that passes from the positive magnetic pole along a line of increasing latitude that passes through the visible rotational pole.

feature caused by the belt can plainly be tracked by eye through the observations of the oxygen triplet over three phases. This irregular secondary belt with its strength concentrated near the rotational equator is reminiscent of the predicted helium feature suggested by Hunger & Groote (1993) for the He peculiar stars. The physical circumstances for ϵ UMa are quite different than those envisioned by Hunger & Groote so the same mechanisms are unlikely to apply but in their paper they suggest an effect whereby some of the Helium selectively expelled by a stellar wind would be guided back to the stellar surface by a combination of Lorentz and inertial forces to create patches trailing the magnetic poles (in a rotational sense) by roughly 45°. Here the secondary feature of enhanced oxygen abundance peaks at less than 45° from the magnetic poles but the features are indeed trailing the magnetic poles in a rotational sense. Thus, in a qualitative sense, the observations here seem to point to selective mass loss as a mechanism for producing the oxygen pattern but the quantitative results for the radiative acceleration on oxygen in Ap star atmospheres argues against this interpretation. Given that Calcium also seems to be in a strong band at the magnetic equator, it would be very interesting to search for a comparable secondary feature in Doppler images based on calcium.

If selective mass loss were to explain the observations for oxygen, it seems that a different explanation would have to be used to explain the chromium observations. For chromium, we have a generally overabundant region near the magnetic pole and a sharply reduced abundance belt around the magnetic equator. A similar abundance distribution may apply to iron but for iron it would seem the abundance is concentrated more strongly to the magnetic pole and there may be a secondary ring at about 70° from the pole (Rice & Wehlau 1990; Donati 1990). For these elements we must presume the radiative accelerations are insufficient to expel the elements from the atmosphere. Abundance enhancement is occurring at the magnetic pole and the enhancing mechanism is less effective near the magnetic equator. The difference in abundance between polar region and equator is generally about three orders of magnitude (see Fig. 3 and Rice & Wehlau (1991)), which is about two orders of magnitude less than the difference for oxygen. At this point we can only ask questions. Is the enhancement near the magnetic poles a result of the horizontal driving mechanisms suggested above? The horizontal component of the radiative acceleration is directed away from the equator in a dipole geometry and the time span available for accumulating regions of enhanced abundance on ϵ UMa is large. Is ambipolar diffusion a factor and is it being suppressed at the equator?

6. Summary

The dramatic variations of the line of the oxygen triple at 7775Å have allowed us to obtain an excellent map of the distribution of the abundance of oxygen over the surface of ϵ UMa. A review of earlier observations of the Cr variation has provided a contrasting map of the Cr distribution over the surface. The combination of these images with the recently determined behaviour of the very weak effective magnetic field variation by Bohlender & Landstreet (1990) has allowed us to determine the location and extent of abundance variations relative to the magnetic field geometry on the assumption that the field is primarily dipolar. Our conclusions are:

1) The centre of abundance symmetry for oxygen (which is presumed to be the location of the positive magnetic pole) is located quite accurately at latitude +28° and longitude 349° using the Provin ephemeris.

2) That the abundance of oxygen is depleted to about [O/H]=-7 in a broad cap at the magnetic pole.

3) There is a belt of oxygen abundance around the magnetic equator where the abundance rises to about [O/H]=-2. This represents an enhancement over the polar regions of five orders of magnitude.

4) There is a pronounced secondary belt of oxygen abundance tilted by about 60° to 70° to the primary belt of oxygen abundance. The abundance in this secondary belt is about three orders of magnitude less than that in the primary belt.

5) Chromium is confirmed as being depleted at the magnetic equator by about three orders of magnitude over the polar regions.

6) Qualitatively the evidence from the oxygen image seems to suggest selective mass loss as the primary mechanism for generating the horizontal abundance variations. All of, the location of the enhancement, the size of the variation and the existence of the secondary belt of abundance may point to this conclusion.

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