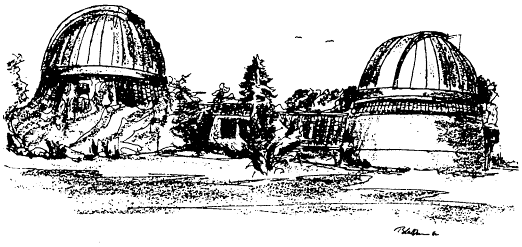
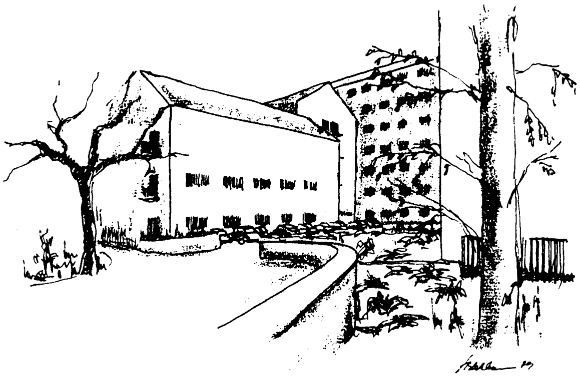
INSTITUTE OF ASTRONOMY
UNIVERSITY OF AARHUS
DK-8000 AARHUS C
DENMARK

AARHUS - ASTRO - 1991 - 1
ISSN 0906-3870





FIRST DETECTION OF BERYLLIUM IN A VERY METAL POOR STAR: A TEST OF THE STANDARD BIG BANG MODEL

G. Gilmore, B. Edvardsson, P.E. Nissen

Abstract

The primordial abundances of ^{9}Be and ^{11}B are the most sensitive indicators of the importance of inhomogeneity in the early universe which have not yet been measured. Additionaly, their abundances in the oldest stars are a sensitive measure of the star formation and cosmic ray spallation history of the early Milky Way. We report here the first determination of the abundance of ^{9}Be in a very metal-poor star, showing that such measurements are possible, and opening the way to a new investigation of the structure of the very early universe and the evolution of the early Galaxy. The star HD140283, which has $[\mathrm{Fe/H}] = -2.6$, has a beryllium abundance of $\log(^{9}\mathrm{Be/H}) = -12.8 \pm 0.3$, a factor of ≈ 1000 greater than the primordial value predicted in the standard model of light element nucleosynthesis.

In press **Astrophysical Journal, Sept 1, 1991**

First Detection of Beryllium in a Very Metal-poor Star: a Test of the Standard Big Bang Model

Gerard Gilmore[1], Bengt Edvardsson[2], P.E. Nissen[3]

[1] Institute of Astronomy, Madingley Rd., Cambridge CB3 0HA, England
[2] Astronomical Observatory, Box 515, S-751 20 Uppsala, Sweden
[3] Institute of Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark

in press, Astrophysical Journal, Sept 1, 1991.

Abstract

The primordial abundances of ^{9}Be and ^{11}B are the most sensitive indicators of the importance of inhomogeneity in the early universe which have not yet been measured. Additionally, their abundances in the oldest stars are a sensitive measure of the star formation and cosmic ray spallation history of the early Milky Way. We report here the first determination of the abundance of ^{9}Be in a very metal-poor star, showing that such measurements are possible, and opening the way to a new investigation of the structure of the very early universe and the evolution of the early Galaxy. The star HD140283, which has [Fe/H]=−2.6, has a beryllium abundance of log (^{9}Be/H)= −12.8 ± 0.3, a factor of ≈ 1000 greater than the primordial value predicted in the standard model of light element nucleosynthesis.

Introduction

The physics of the QCD phase transition from quark domination to baryon domination in the early universe has recently been shown to have potentially observable consequences for the abundances of several of the light elements. This new appreciation stems from a realisation (Witten 1984) that the quark-hadron phase transition is likely to have been first order, so that density perturbations would result. These density inhomogeneities might have a significant effect on later nucleosynthesis (Applegate & Hogan 1985). Also a reassessment of the nuclear reaction paths of relevance for ^{9}Be and ^{11}B (Boyd & Kajino 1989) showed that the primordial abundances of these two light elements were both potentially many orders of magnitude larger than had been believed, and were also sensitive to inhomogeneities on scales of interest. Measurements of the relative abundances of ^{9}Be and ^{11}B additionally allows discrimination between primordial and subsequent Galactic production of these light elements.

Chiral perturbation QCD calculations (see *e.g.,* Mariani & Bonometto 1990 for a recent discussion) suggest that the phase transition occurred at a temperature of $\sim$ 200MeV, when the Universe was approximately 20μs old. Any resulting density inhomogeneities should survive to the epoch (T$\sim$ 1MeV, time $\sim$ 1s) at which the initial conditions for the nucleosynthesis period were fixed, and might have a measurable effect on the later

nucleosynthetic yields (see Thielemann & Wiescher 1990 for a recent review). The effect on nucleosynthesis occurs since neutrons are able to diffuse out of the high density regions while (charged) protons are not. Most calculations suggest density contrasts with a characteristic scale length within a few orders of magnitude of 1 metre at the phase transition. This corresponds to a few km at the onset of nucleosynthesis and would be $\sim$ 10 AU now, though fluctuations of this scale are unlikely to survive until recombination.

Detailed predictions of the physical properties of the quark-hadron phase transition(s) remain uncertain, and extant calculations of the predicted abundances of the (potentially) measurable light elements (^{2}H, ^{3}He, ^{4}He, ^{7}Li, ^{9}Be, and ^{11}B) in inhomogeneous models are in significant disagreement. Many models have illustrated the sensitivity of the resulting elemental yields to the amplitude and length scales assumed, and the details of neutron diffusion adopted, with predictions of the ^{9}Be abundance ranging from 3 orders of magnitude below that of the standard model to 4 orders of magnitude above. The ratio of ^{9}Be to ^{11}B abundances expected is also uncertain. Most models predict an abundance of ^{9}Be which is roughly a factor of ten greater than that of ^{11}B. Malaney & Fowler (1990), however, describe conditions where the primordial ratio mimics that of spallation production. Recent work, particularly that by Terasawa & Sato (1990) has emphasised the extreme sensitivity of the expected abundances to details of the late-time back-diffusion of neutrons into the (formerly) proton-rich material. Their work shows that available models remain schematic rather than rigorous in their treatment of the spatial and temporal properties of the inhomogeneities and the neutron and proton diffusion, so that conclusions remain suggestive rather than robust.

Thus there is no guarantee that primordial ^{9}Be is detectable even in a quite inhomogeneous universe. Were it detected however, parameter space for all models of primordial nucleosynthesis would be severely restricted, the baryon density Ω_B would be known with greater reliability than it is at present, and the physics of the phase transition at the end of the quark-dominated era of the Universe would be available for study. We report here the first measurement of the abundance of Be in a very metal-poor star, showing that such measurements are indeed possible, and opening the way to a new investigation of the evolution of the very early Universe.

Observations

The light elements of cosmological significance can be destroyed and (in some cases) created during normal stellar evolution. Complications due to this are particularly acute for ^{7}Li, where the observed abundance is a strong function of stellar temperature and evolutionary state (see Boesgaard & Steigman 1985; Smith & Lambert 1989; Mathews, Alcock, & Fuller 1990; Deliyannis, Demarque, & Kawaler 1990; and Reeves, Richer, Sato & Terasawa 1990 for representative recent discussions). ^{9}Be and ^{11}B are both more robust to destruction during stellar evolution than is ^{7}Li, and are probably created in fewer astrophysical environments. Thus, restricting the sample of stars utilised for determination of the abundances of ^{9}Be and ^{11}B to those stars in which ^{7}Li is near to its primordial value (here assumed to be $(N_{\rm Li}/N_{\rm H}) \sim 2\times10^{-10}$ following Deliyannis *et al.* 1990) will minimise changes in the photospheric abundances of the light elements which are caused by the specific evolutionary history of a specific star, and will maximise the likelihood that the observed abundances truly represent the abundances of the inter-stellar medium at the time the star formed. For present conservative purposes this restricts the range of interest to F/G stars which are on or near to the main sequence, and which have [Fe/H] $\lesssim -1.5$ (*c.f.* Rebolo *et al.* 1988a; Mathews, Alcock & Fuller 1990).

No measurements of the abundance of ^{9}Be exist for stars with metallicity [Fe/H]$\lesssim -1.3$, though upper limits exist for six stars with $-2.6 \gtrsim$ [Fe/H] $\gtrsim -1.3$ (Ryan *et al.* 1990; Rebolo *et al.* 1988b). The most metal-poor of these stars, for which Ryan *et al.* (1990) derive an upper limit to the ^{9}Be abundance of $\log(N_{^9\mathrm{Be}}/N_\mathrm{H}) \leq -13.2$, is HD140283, an apparently bright (V= 7.2), relatively unevolved (a subgiant, $\log g = 3.6$), and very metal-poor star ([Fe/H]=−2.6). We have obtained new spectra with higher resolution (R≈ 75000) and signal-to-noise ratio (S/N≈ 20) than were previously available for this star, and detect both the ^{9}Be lines, at 3130.42Å and 3131.06Å. Thus we are able to derive a measured abundance, rather than a limit.

The spectra were obtained during service observations at the Anglo-Australian Telescope, with a 0.65 arcsec slit, the coude echelle spectrograph (UCLES), and an IPCS detector. Four 1800sec integrations interspersed with ThAr arc exposures were obtained in photometric conditions, but with 1.5arcsec seeing. The echelle slit was sufficiently long to allow adjacent sky to be subtracted. In considering the possibility of contamination of the weak beryllium lines in HD140283 by the very strong solar beryllium lines, it is helpful to remember that the star's radial velocity is such that the stellar spectrum is offset by 1.67Å from the sky spectrum, which was in any case mostly scattered light and dark count. Thus no residual contamination is suspected. The four separate integrations are shown in Figure 1.

Analysis

The two BeII lines are seen in each of the individual spectra in Fig. 1, and stand out clearly in the summed spectra shown in Fig. 2. Misidentification with other spectral features expected in this wavelength range (see below) is improbable, and pure noise or instrumental effects can be excluded. We regard the identification of the two BeII lines in HD140283 as very probable.

The analysis is a standard LTE analysis. The model atmospheres were calculated with a new version of the program described by Gustafsson *et al.* (1975). The main difference relative to the old version is the inclusion of millions of metal lines in the UV - blue wavelength region. These lines (from neutral and singly ionized lines of Ca, Sc, Ti, V, Cr, Mn, Fe, Co and Ni) were taken from the new semiempirical calculations of Kurucz (1989). The effect of the inclusion of these lines is seen in the resulting model temperature structure and in a much better agreement with observed fluxes for the Sun (Edvardsson et al., 1991).

The parameters adopted for the model for HD140283 are: T_eff=5640 (Magain, 1989; Zhao, 1990), logarithmic iron abundance relative to the Sun; [Fe/H]=−2.6 (Zhao, 1990), and microturbulence parameter $\xi_t = 1.5$ km/s (Zhao, 1990). The surface gravity, $\log g$=3.6, was interpolated from the 16 Gyr isochrones of VandenBerg and Bell (1985), assuming that the star is a sub-giant; the position of the star in the Strömgren c_1-(b-y) diagram supports this assumption (in variance to what may be inferred from its uncertain parallax and apparent magnitude). A number of models with varied parameters were also constructed in order to study the effects of uncertainties in the adopted model parameters.

Synthetic spectra were calculated with line data from the following sources:
BeII: absolute laboratory oscillator strengths from Wiese & Martin (1980), CH: Moore & Broida (1959a), OH: Moore & Broida (1959b), Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni from Kurucz (1989), Y, Zr, Tm from Kurucz & Peytremann (1975).
The oscillator strengths of the identified lines (except for beryllium) were found from fits of a synthetic spectrum to the Solar spectrum observed by Kurucz et al. (1984). For the several hundreds of weak lines from Kurucz (1989), the oscillator strengths were kept unchanged, and it was observed that their inclusion significantly depresses the "high" flux points in the solar synthetic spectrum, thereby improving the fit. It must still be kept in mind that the assumed continuum level of the Solar observations may be wrong. The Solar chemical abundances were adopted from Anders & Grevesse (1989), whose solar beryllium abundance (log(Be/H)=−10.85) in turn comes from Chmielewski, Muller & Brault (1975).

The chemical abundances in HD140283 of most elements were assumed to follow the iron abundance in the proportions they have in the Sun. Exceptions were oxygen: [O/Fe]=+0.5 was taken as quoted by Ryan *et al.* (1990), supported by NLTE calculations by Kiselman (1991); and titanium: [Ti/Fe]=+0.35 as quoted by Ryan *et al.* (1990). To account for the instrumental profile of the observations of HD140283 the synthetic spectra were convolved with a Gaussian with a FWHM of 0.085Å.

Figure 2 shows the final fit to the Solar spectrum (upper panel) and the summed, mean sky level subtracted, spectrum of HD140283 and spectra from the standard model with three values of $\log \mathrm{Be/H}$ (*i.e.*, $\log N_\mathrm{Be}/N_\mathrm{H}$) (lower panel). The best fit is found for $\log \mathrm{Be/H} = -12.8$, with an uncertainty in the fit of ±0.3 dex.
The sensitivity of this result to variations in the model parameters is:

$\Delta T_\mathrm{eff} = -100$K: implies $\Delta \log \mathrm{Be/H} = -0.05$ dex,
$\Delta \log g = -0.40$: implies $\Delta \log \mathrm{Be/H} = -0.2$ dex,
Δ [Fe/H] $= +0.30$ dex: implies $\Delta \log \mathrm{Be/H} = -0.05$ dex,
$\Delta \xi_t = +0.5$ km/s: implies $\Delta \log \mathrm{Be/H} = 0.0$ dex.

A pessimistic estimate of the uncertainty in the result due to errors in the model parameters (200 K in T_eff, 0.5 dex in $\log g$, 0.3 in [Fe/H]) is ±0.27 dex. In view of the fact that BeII is the dominant ionization stage of Be, and that the lines observed are weak resonance lines, we believe the effects of departures from LTE and of thermal convective inhomogeneities to be small. Our final estimated maximum error in the beryllium abundance of HD140283 is thus 0.4 dex.

The Galactic Evolution of ^{9}Be

Before any cosmological interpretation of a measured ^{9}Be abundance is possible, it is essential to know the contributions to the measured value from subsequent Galactic production and destruction. ^{9}Be is destroyed, by burning at $\sim 3.6 \times 10^6$K, and is created, by spallation of cosmic ray protons and α−particles onto CNO nuclei. The first of these processes means that ^{9}Be will be destroyed in stars with suitably deep convective zones, while the second means that it is created at a rate which depends on both the heavy element abundance of the interstellar medium and the energy spectrum of cosmic rays in the early Milky Way. Fortunately, other sensitive indicators of the rate of both these processes are available, in the abundances of ^{7}Li and ^{11}B, so they may be quantified to some extent.

^{7}Li is created in the Big Bang, and also in cosmic ray spallation, as well as in several other astrophysical environments (*c.f. e.g.,* Smith & Lambert 1989 and Mathews *et al.* 1990 for recent discussions). It is destroyed by burning at $\sim 2.5 \times 10^6$K. Thus it is more sensitive to the rate of stellar destruction of the light elements than is ^{9}Be (see *e.g.,* Boesgaard & Budge 1989). ^{11}B is created in small quantities in inhomogeneous Big Bang models (Boyd & Kajino 1989; Malaney & Fowler 1989), and also is created with ^{9}Be in cosmic ray spallation (Walker, Mathews, & Viola 1985) and possibly with ^{7}Li in supernovae (Dearborn *et al.* 1989). Inhomogeneous Big Bang models typically predict that about one order of magnitude more ^{9}Be than ^{11}B is produced (Boyd & Kajino 1989, but *c.f.* Malaney & Fowler 1989). Current spallation models, while both uncertain and at best a moderate fit to observational data, predict about one order of magnitude more ^{11}B than ^{9}Be. Additional production of ^{11}B in other astrophysical environments can only increase this relative overproduction.

It is apparent from these production and destruction rates that comparison of the relative abundances of all of ^{7}Li, ^{9}Be, and ^{11}B can provide a direct test of the primordial or galactic origin of the ^{9}Be abundance in metal poor stars. Specifically, if one restricts attention to stars in which ^{7}Li is observed to be at or near its primordial value then one may assume that substantial net *destruction* of ^{9}Be has not taken place. If one then finds that ^{9}Be is significantly more abundant than is ^{11}B in that star, one may conclude that substantial net *creation* of ^{9}Be has not taken place subsequent to primordial nucleosynthesis. Additionally, if the measured ^{9}Be abundance is both primordial and significantly exceeds a value of $\sim 2 \times 10^{-16}$, then one has evidence that inhomogeneities have had a detectable effect on the physical conditions in the early universe during the time of nucleosynthesis. ^{11}B is measurable only from an absorption line at 2496Å, accessible in HD140283 uniquely but straightforwardly with the Hubble Space Telescope.

The question then arises if HD140283 really does have the primordial abundance of ^{7}Li? The Galactic evolution of ^{7}Li is a complex and unresolved problem (see Boesgaard & Steigman 1985; Mathews *et al.* 1990; and refs therein). However, according to Rebolo *et al.* (1988a), dwarf and subgiant stars with $[\mathrm{Fe/H}] \lesssim -1.5$ and $5500\mathrm{K} \lesssim T_{\mathrm{eff}} \lesssim 6300\mathrm{K}$ have an average Li abundance of $N_{\mathrm{Li}}/N_{\mathrm{H}} \approx 1.2 \times 10^{-10}$, independent of their value of [Fe/H]. The data of Rebolo *et al.* show a slight trend towards $N_{\mathrm{Li}}/N_{\mathrm{H}} \approx 1.6 \times 10^{-10}$ at $T_{\mathrm{eff}} = 6300$K, which ratio is conventionally adopted as the primordial value. HD140283 has $[\mathrm{Fe/H}]=-2.6$ and $N_{\mathrm{Li}}/N_{\mathrm{H}} = 1.1 \pm 0.5 \times 10^{-10}$ (Rebolo *et al.* 1988a), which agrees with the primordial value within the estimated uncertainty.

It is still possible that the abundance of ^{9}Be may be strongly enhanced over its primordial value, even though the abundance of ^{7}Li is not enhanced, if there is a source of ^{9}Be which does not create measurable Li. Such a source *could* exist, in cosmic ray spallation with an appropriate energy spectrum. Current calculations of the relative production rates of ^{7}Li, ^{9}Be, and ^{11}B in cosmic ray spallation predict relative abundances of 6:1:12 for the energy spectrum which predicts the greatest relative amount of ^{9}Be (see Table 2 of Walker, Mathews & Viola 1985). Creation of a factor of 1000 more ^{9}Be, to bring the homogeneous Big Bang prediction up to the observed abundance in HD140283, would still correspond to an immeasurably small increase ($\sim 1\%$) in the spallation abundance of ^{7}Li, as ^{7}Li is so relatively abundant already. [Any model of this type must be reconciled with the calculations of Dearborn *et al.* (1989), who show that the supernovae which create the oxygen which will later be spalled, and which most likely also accelerate the cosmic rays, would create significant quantities of ^{7}Li as well.] Thus no direct test of the primordial abundance of ^{9}Be is available from this single measurement. The abundance of ^{11}B would however also be increased from the homogeneous big bang prediction of $^{11}\mathrm{B}/^9\mathrm{Be} \sim 0.1$ to $^{11}\mathrm{B}/^9\mathrm{Be} \sim 10$. Determination of this element ratio in HD140283 is clearly of considerable interest.

A reliable determination of the primordial beryllium abundance will require extension of the present results to include stars with a variety of [Fe/H] metallicities, to see if a constant ^{9}Be/H ratio is reached, in the same way as is seen for ^{7}Li/H. Additionally it requires measurement of $^{11}\mathrm{B}/^9\mathrm{Be}$ ratios, to ascertain the relative contributions of primordial nucleosynthesis and cosmic ray spallation to the abundances of the light elements in metal poor stars. Attempts to observe additional Be lines, such as the BeI line at 2348.61Å, could also be significant. Current attempts to generalize Galactic chemical evolution models to describe the evolution of ^{9}Be, even when explicitly allowing for the effects of cosmic ray spallation (Vangioni-Flam *et al.* 1990) are considerably at variance with the observed abundance in HD140283, in that the observed abundance exceeds the prediction by a large factor. While this is not inconsistent with an enhanced primordial production of ^{9}Be, it may well more prosaically identify limitations in current chemical evolutionary models.

Conclusion

An important consequence of the measurement of the abundance of ^{9}Be in HD140283, of $\log(^9\mathrm{Be/H}) = -12.8 \pm 0.3$ at $[\mathrm{Fe/H}]=-2.6$, is that it proves that one can detect measurable quantities of light elements which are sensitive probes of the physical conditions in the early universe and the early galaxy, in addition to those which have been extensively studied to date. The additional information provided by beryllium and boron can allow unambiguous tests of both the inhomogeneity generated in the early universe at the quark-hadron phase transition and the chemical and cosmic ray evolution of the early galaxy.

Acknowledgements

We wish to thank Kjell Eriksson and Bengt Gustafsson for valuable discussions and suggestions, and Jason Spyromilio for obtaining the AAT spectra as a service observation.

References

Anders, E., Grevesse, N. 1989, Geochimica et Cosmochimica Acta, **53**, 197

Applegate, J. & Hogan, C. 1985, Phys. Rev. D, **31**, 3037

Boesgaard, A. & Steigman, G. 1985, Ann. Rev. Astr. Ap., **23**, 319

Boesgaard, A. & Budge, K. 1989, ApJ, **338**, 875

Boyd, R.N. & Kajino, T. 1989, ApJ, **336**, L55

Chmielewski, Y., Muller, E.A., & Brault J.W. 1975, Astr.Ap., **42**, 37

Dearborn, D.S., Schramm, D., Steigman, G., & Truran, J. 1989, Ap.J., **347**, 455

Deliyannis, C., Demarque, P. & Kawaler, S. 1990, ApJSuppl, **73**, 21

Edvardsson, B., Gustafsson, B., Lambert, D.L., Nissen, P.E., Tomkin, J., & Andersen, J. 1991, in preparation

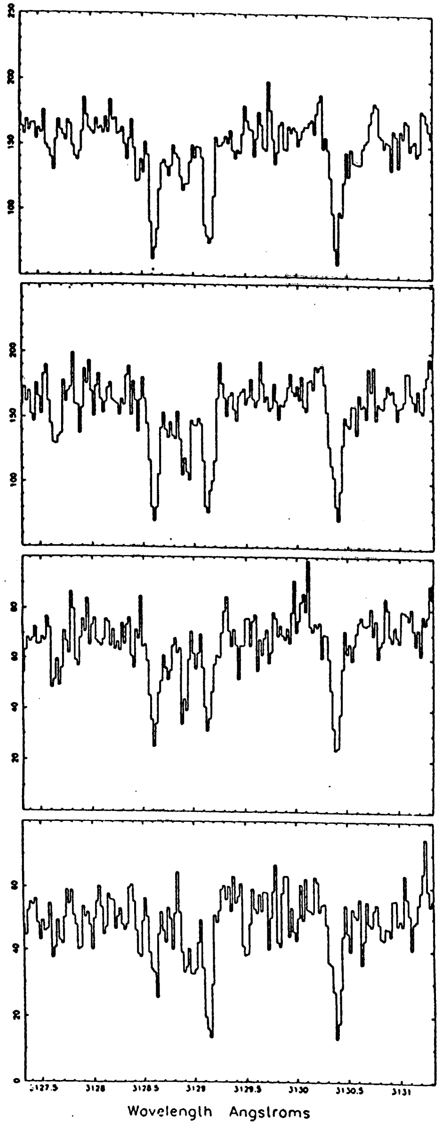
Gustafsson, B., Bell, R.A., Eriksson, K., Nordlund, Å. 1975, Astr.Ap. **42**, 407

Kiselman, D. 1991, in preparation
Kurucz, R.L. 1989, private communication
Kurucz, R.L. Peytremann, E. 1975, "A Table of Semiempirical *gf* values", Smithsonian Astrophys. Obs. Spec. Rep. No. 362
Kurucz, R.L., Furenlid, I., Brault, J., Testerman, L. 1984, "Solar flux atlas from 296nm to 1300nm", National Solar Observatory, Atlas No. 1
Magain, P. 1989, Astr.Ap., **209**, 211
Malaney, R.A. & Fowler, W. 1989, ApJ, **345**, L5
Mariani, M., & Bonometto, S.A. 1991, ApJ, in press
Mathews, G.J., Alcock, C., & Fuller, G. 1990, ApJ, **349**, 449
Moore, C.E., Broida, H.P. 1959a, J. Res. Nat. Bureau of Standards, **63A**, 19
Moore, C.E., Broida, H.P. 1959b, J. Res. Nat. Bureau of Standards, **63A**, 279
Rebolo, R., Molaro, P., & Beckman, J. 1988a, Astr.Ap., **192**, 192
Rebolo, R., Molaro, P., Abia., C. & Beckman, J. 1988b, Astr.Ap., **193**, 193
Reeves, H., Richer, J., Sato, K. & Terasawa, N. 1990, ApJ, **355**, 18
Ryan, S.G., Bessel, M.S., Sutherland, R.S., Norris, J.E. 1990, ApJ, **348**, L57
Smith, V. & Lambert, D. 1989, ApJ, **345**, L75
Terasawa, N. & Sato, K. 1990, ApJ, **362**, L47
Thielemann, F. & Wiescher, M. 1990 in Primordial Nucleosynthesis, eds W. Thompson & B. Carney, in press.
VandenBerg, D.A., Bell, R. 1985, ApJSuppl, **58**, 561
Vangioni-Flam, E., Cassé, M., Audouze, J., & Oberto, Y. 1990, ApJ, **364**, 568
Walker, T.P., Mathews, G.J., & Viola, V.E., 1985, ApJ, **299**, 45
Wiese, W.L., Martin, G.A. 1980, in "Wavelengths and Transition Probabilities for Atoms and Atomic Ions" (NSRDS-NBS 68) (Washington: US Government Printing Office), p. 359.
Witten, E., 1984, Phys. Rev. D, **30**, 272
Zhao, G. 1990, Thesis, Nanjing University and European Southern Observatory

Figure captions

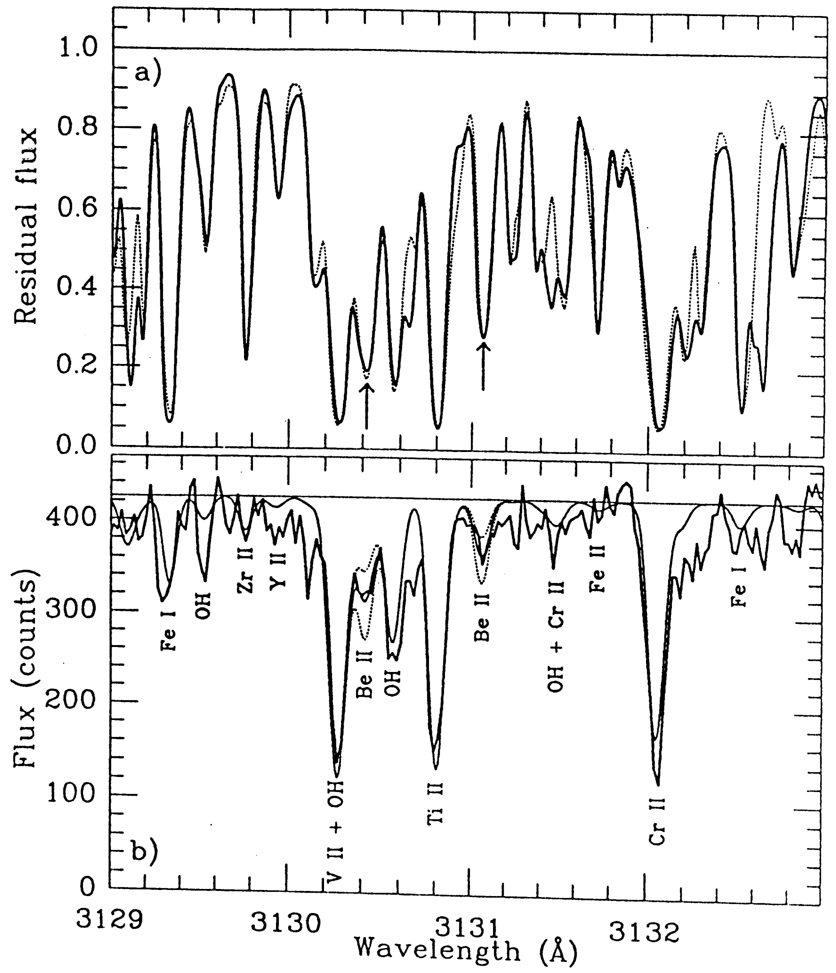
Figure 1. The four individual spectra, rebinned onto a linear wavelength scale, but not corrected to rest wavelength or sky subtracted. The 'sky' background, which is dominated by featureless scattered light, is in each spectrum closely 10% of the number of continuum counts near the BeII lines. The observed (blue-shifted) positions of the ^{9}Be lines are 3128.75Å, and 3129.39Å. The vertical scale in each spectrum is photon counts, and the variation in signal-to-noise ratio of the spectra reflects changes of seeing.

Figure. 2. a) The observed Solar spectrum (Kurucz et al., 1984) and a synthetic spectrum with oscillator strengths of identified lines adjusted to fit (NB: the BeII oscillator strengths are absolute). The BeII lines are indicated by arrows. b) The sum of the four spectra of HD140283 with the mean sky level subtracted. Thin and dotted lines: synthetic spectra from a model with parameters $T_{\rm eff}/\log g/[{\rm Fe/H}]/\xi_t = 5640/3.6/-2.60/1.5$, and three different values of log Be/H: -12.6, -12.8 and -13.0. A few of the strongest lines in the synthetic spectra are identified.



250
200
150
100
200
150
100
80
60
40
20
60
40
20
0
3127.5
3128
3128.5
3129
3129.5
3130
3130.5
3131
Wavelength Angstroms

Fig. 1



Residual flux
1.0
0.8
0.6
0.4
0.2
0.0
a)
Flux (counts)
400
300
200
100
0
b)
Fe I
OH
Zr II
Y II
V II + OH
Be II
OH
Ti II
Be II
OH + Cr II
Fe II
Cr II
Fe I
3129
3130
3131
3132
Wavelength (Å)

Fig. 2