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ζ^1 and ζ^2 Reticuli and the existence of the ζ Herculis group[⋆]

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Abstract. We report the detailed analysis of the solar type stars ζ^1 and ζ^2 Reticuli. We obtained accurate effective temperatures ($T_{\rm eff}$ = 5746 ± 27 K and 5859 ± 27 K respectively) and surface gravities (log g = 4.54 ± 0.02 and 4.46 ± 0.01 respectively). Both stars are slightly metal deficient ([Fe/H] = −0.22 ± 0.05) and their element abundance patterns are compatible with one another and with the Sun.

The hypothesis, suggested by previous detailed analyses, that these stars could be helium rich relative to the Sun, was investigated. The stars were found to have a normal, solar helium abundance.

We analysed the stars' membership of the ζ Herculis stellar kinematic group (SKG). Some probable members have nearly the same galactic orbital parameters, chemical composition and evolutionary states, which confirm the existence of a metal deficient SKG. Since we determined that ζ Herculis does not belong to this group, we propose it be renamed ζ Reticuli SKG.

Key words: stars: fundamental parameters – stars: abundances – stars: chemically peculiar – Galaxy: open clusters and associations: individual: ζ Herculis stellar kinematic group

1. Introduction

ζ^1 and ζ^2 Reticuli form a striking couple of dwarf stars because they present some contradictory properties. As judged from their kinematical parameters they are very likely old disk population stars (Eggen, 1971). However ζ^1 Ret presents emission in the Ca II H and K lines with a strength that is typical of the young disk population. A previous paper (da Silva & Foy, 1987) put them under the zero age main sequence (ZAMS) corresponding to their metallicity. The similarities between their kinematical characteristics and the little distance that separates them from each other (310″ or $0.048^{+0.144}_{-0.029}$ pc) hint at a common origin for these stars.

ζ^1 and ζ^2 Reticuli are classified as G3-5 V and G2 V, respectively, according to the Michigan Catalogue of Spectral Types (Houk & Cowley, 1975). They have common proper motions and radial velocities. Da Silva & Foy (1987), who made a detailed spectroscopic analysis of these stars, found for both of them a high surface gravity (log g = 4.70) typical of metal deficient, unevolved stars. Their gravity was determined based on the $T_{\rm eff}$ obtained by the authors and on the parallax values available at the time. In spite of their high surface gravity, the metal content determined by them for these stars was a bit higher than the solar one ([Fe/H] = +0.10, with the usual notation [A/H] = $\log(A/H)_* - \log(A/H)_\odot$). This discrepancy could be explained, according to the authors, if the stars were helium rich, relatively to the Sun (Perrin et al., 1977).

Woolley (1970) has proposed that these two stars belong to the ζ Herculis kinematic group defined by Eggen (1958). Porto de Mello & da Silva (1991) studied the physical existence of this group on the basis of an abundance analysis. For this purpose they used the ζ^1 and ζ^2 Ret abundances determined by da Silva and Foy. However, there are great discrepancies between different authors who have analysed these stars. The effective temperatures determined for ζ^2 Ret, for example, range from 5600 K to 6072 K. This variation is 3 times larger than the probable errors cited for the determinations. The determined iron abundances ([Fe/H]) present a variation of 0.52 dex between different authors. Precise determinations of these atmospheric parameters are needed to obtain accurate abundances and to analyse the evolutionary stage of the stars by way of evolutionary diagrams and isochrones, thus determining if ζ^1 and ζ^2 Ret belong or not to the ζ Her group.

In the present analysis we seek to obtain the atmospheric parameters and element abundances of ζ^1 and ζ^2 Ret with as high a precision as possible. Using these data we study the evolutionary stage of these stars to verify the hypothesis of helium superabundance. We finally analyse the physical existence of the ζ Her kinematic group.

2. Observations and data reduction

2.1. Observations

CCD spectra of the sky, ζ^1 and ζ^2 Reticuli were obtained in September 1991 at the European Southern Observatory (ESO).

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[⋆] Based on observations collected at the European Southern Observatory, La Silla, Chile, and at the Observatório do Pico dos Dias, operated by the Laboratório Nacional de Astrofísica, CNPq, Brazil.

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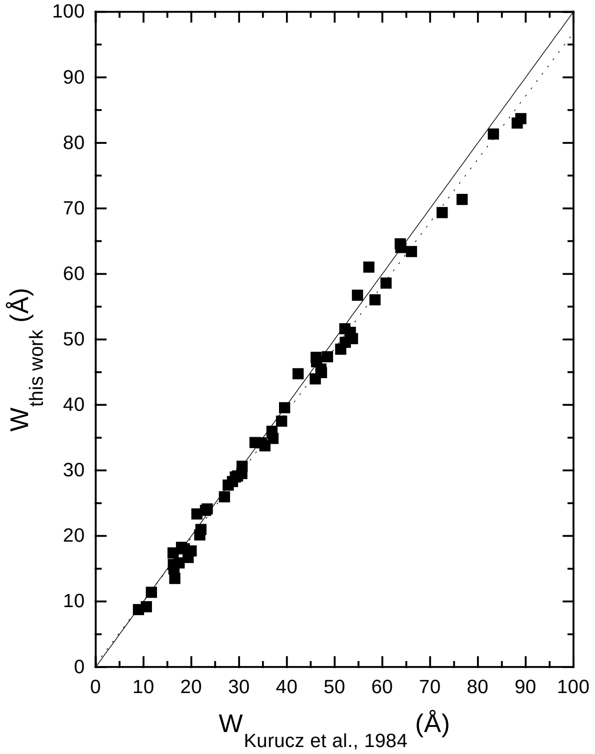

Fig. 1. Comparison between sky equivalent widths (this work) and the Kurucz et al. (1984) solar atlas equivalent widths for all measured atomic lines. Dotted line is a linear fit.

The observations were carried out with the Coudé Echelle Spectrograph (CES) fed by the 1.40 m Coudé Auxiliary Telescope (CAT). The spectra comprised 5 regions, centered at 4370 Å, 4560 Å, 4860 Å (H_β), 6110 Å and 6500 Å, covering 35–55 Å each. Complementary Reticon spectra, centered at 6240 Å and 6720 Å and covering 50 Å each, were observed with the same spectrograph and telescope in February 1992. The estimated S/N ratios for all these spectra ranged from 300 to 400. Their resolution was from 0.090 to 0.135 Å (resolving power R $\simeq$ 50 000).

CCD spectra centered in the H_α line (6563 Å), and covering 150 Å each, were obtained in 1994 and 1995 with the coudé spectrograph fed by the 1.60 m telescope of the Observatório do Pico dos Dias (CNPq/LNA, Brazil). These spectra had a S/N ratio of 200 and a resolution of 0.330 Å (resolving power R $\simeq$ 20 000).

2.2. Data reduction and determination of equivalent widths

Bias extraction, flat fielding, linearization and wavelength calibration were carried out in the conventional way using the IRAF reduction package on a SUN workstation. Once corrected of Doppler shifts the spectra were normalized by fitting the mean flux in selected continuum windows, identified by comparison with the solar spectrum atlas of Kurucz et al. (1984), with low ($\leq$ 4) order polynomials. The average internal deviation of the continuum fitting was 0.2%.

We have selected the stellar lines to be measured according to the compilation of Moore et al. (1966). Measurements of the equivalent widths were accomplished by least-squares gaussian fittings. The fitting of up to 4 gaussians simultaneously allowed us to successfully obtain equivalent widths of moderately blended lines, unresolved lines being rejected. We checked the accuracy of our measuments by comparing our solar equivalent widths with those of the atlas of Kurucz et al. (1984). The comparison (Fig. 1) is excellent, with a linear fit of high correlation (R = 0.996) and low standard deviation (σ = 1.7 mÅ). No systematic deviations have been found.

3. Analysis and results

Atmospheric parameters and element abundances have been derived using the plane parallel, flux constant, LTE model atmospheres described and discussed in detail by Edvardsson et al. (1993). In order to perform a differential analysis relative to the Sun these models have been used for both the analysed stars and the Sun. The adopted solar atmospheric parameters were $T_{\rm eff}$ = 5777 K (Neckel, 1986), log g = 4.44, [Fe/H] = 0.00, ξ = 1.00 km s^{-1} and n(He)/n(H) = 0.10.

Gf-values were derived from solar equivalent widths, measured on solar spectra taken in the same conditions as the stellar ones, by forcing the calculated solar element abundances to agree with those determined by Anders & Grevesse (1989), and Grevesse & Noels (1993). This ensures the differential character of our analysis.

3.1. Atmospheric parameters

3.1.1. Effective temperatures

The effective temperatures have been derived by four independent criteria: excitation equilibrium, photometric indices calibration and fitting of H_α and H_β profiles. The excitation equilibrium has been determined through the analysis of the Fe I lines. Using the model atmospheres, "solar" gf values and atomic data we calculate the iron abundances line by line, using a program kindly supplied by M. Spite (Observatoire de Paris-Meudon, France). The theoretical abundance for a given line is changed iteratively until the obtained equivalent width equals the measured one. If the effective temperature is correct the abundance of Fe should be independent of the excitation potential of the lines. So if we plot an iron abundance vs. excitation potential graph for all Fe I lines and fit a straight line, this line should present a negligible (within the expected error) angular coeficient. If a significant positive or negative slope is measured, the model effective temperature is increased or decreased, respectively, and the iron abundances recalculated. The effective temperatures determined by this method are hereafter designated *excitation temperatures*.

We estimated a 55 K probable error for the excitation temperatures by changing the model atmosphere temperature until the angular coeficient of the linear fit equalled the error of its determination.

Table 1. Photometric data for ζ^1 and ζ^2 Reticuli (in the Johnson and Strömgren systems).

	ζ^1 Reticuli	ζ^2 Reticuli
HD	20766	20807
HR	1006	1010
Spectral type	G3-5 V	G2 V
π (mas)	82.5	82.8
V	5.54	5.24
(B−V)	0.64	0.60
(V−K)	1.53	1.42
(R−I)	0.34	0.34
(b−y)	0.402	0.380
β	2.586	2.592

References: Spectral type - Michigan Catalogue of Spectral Types (Houk & Cowley, 1975); Parallax - Hipparcos catalogue (ESA, 1997); V, (B−V), (R−I) - Hoffleit & Jaschek (1982); (V−K) - Koornneef (1983); (b−y) and β - Grønbech & Olsen (1976; 1977).

Table 2. Effective temperatures according to four criteria.

Effective temperatures (K)	ζ^1 Reticuli	ζ^2 Reticuli
Excitation equilibrium	5747 ± 55	5847 ± 55
Photometric calibrations	5746 ± 70	5858 ± 70
H_α profile	5752 ± 45	5877 ± 45
H_β profile	5740 ± 45	5854 ± 45
AVERAGE	5746 ± 27	5859 ± 27

We derived effective temperature estimations from the (B−V), (b−y), (V−K), (R−I) and β photometric indices using the calibrations by Porto de Mello (1996) for solar-type stars, which take into account the stars' metallicities. According to the author of the calibrations the use of 5 different indices simultaneously warrants a probable error as low as 70 K. Table 1 summarizes photometric data for ζ^1 and ζ^2 Ret.

The H_α and H_β profiles have been shown, in the case of cool stars, to be rather insensitive to surface gravity, microturbulence velocity and metallicity variations, at least for quasi-solar abundance stars (da Silva, 1975; Gehren, 1981; Fuhrmann et al., 1993). For the early G stars these profiles are, notwithstanding, very sensible to the effective temperature of the atmosphere. By comparing the theoretical profiles with the observational ones we can estimate the temperatures (Fig. 2). A program kindly made available by Praderie (1967) was used to compute the Balmer lines theoretical profiles. It takes into account the convolution of Stark, Doppler and self-resonance broadenings. Stark broadening has been computed using the method of Vidal et al. (1971), and self-resonance broadening has been included according to the prescription of Cayrel & Traving (1960). The probable internal error of these determinations, reflecting the uncertainties of the continuum determination and personal judgment of the fitting of the observed profiles, is estimated by us as being 45 K.

The adopted effective temperatures of ζ^1 and ζ^2 Ret were calculated by averaging the four previously cited estimations (Table 2). The probable error of the adopted temperatures is 27 K, calculated using the known expression for the probable error of an average of independent estimations. The standard deviations of the four criteria are 5 K for ζ^1 Ret and 13 for ζ^2 Ret, which demonstrates the excellent internal agreement.

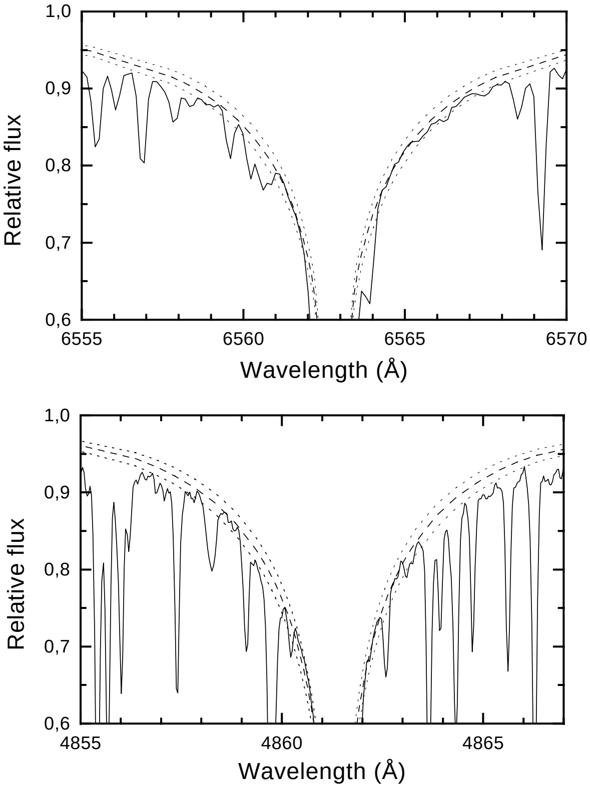

Fig. 2. H_α and H_β profiles of ζ^1 Reticuli. Dashed lines are the best fits. Dotted lines show the profiles computed when the adopted effective temperatures are changed by −100 K and +100 K.

3.1.2. Surface gravities

The surface gravities have been derived by three criteria: ionization equilibrium and using the astrometric parallaxes with masses obtained from a mass-luminosity relation and from evolutionary tracks. We obtained spectroscopic surface gravities by requiring that the ionization equilibrium be satisfied. When this happens, the abundances derived from the lines of ionized and neutral species of any element should be equal. We changed the model atmosphere surface gravity until the iron abundances derived from Fe I and Fe II lines matched. We also required the Ti I and Ti II abundances to match. The logaritmic gravities have an estimated probable error of 0.07 dex for ζ^1 Ret and 0.03 dex for ζ^2 Ret. These errors have been estimated by changing the model atmosphere surface gravity until the ionization equilibrium was no longer verified at the 1σ level.

We also obtained surface gravity estimations using the stellar effective temperatures determined by us, luminosities and masses. To obtain the absolute bolometric magnitudes we used apparent visual magnitudes from Hoffleit & Jaschek (1982), with parallaxes from the Hipparcos catalogue (ESA, 1997) and

Table 3. Surface gravities according to three criteria.

Log g	ζ^1 Reticuli	ζ^2 Reticuli
Ionization equilibrium	4.60 ± 0.07	4.42 ± 0.03
Mass-lum. relation	4.52 ± 0.02	4.49 ± 0.02
Evol. trajectories	4.50 ± 0.02	4.46 ± 0.02
AVERAGE	4.54 ± 0.02	4.46 ± 0.01

Table 4. Adopted stellar parameters for ζ^1 and ζ^2 Reticuli.

Parameter	ζ^1 Reticuli	ζ^2 Reticuli
$T_{\rm eff}$ (K)	5746 ± 27	5859 ± 27
log g	4.54 ± 0.02	4.46 ± 0.01
ξ (km s^{-1})	1.20 ± 0.19	1.02 ± 0.14
[Fe/H]	-0.22 ± 0.05	-0.22 ± 0.05

the Habets & Heintze (1981) bolometric corrections. The latter were adjusted so that the solar absolute bolometric magnitude was $\rm M_\odot = 4.75$. Masses were derived using either the Böhm (1989) mass-luminosity relation for main sequence stars or the Schaller et al. (1992), Schaerer et al. (1993) and Charbonnel et al. (1993) (hereafter Gen92/93) evolutionary trajectories. The gravities were calculated according to the known equation

$$\frac{\rm g_*}{\rm g_\odot} = \frac{\rm m_*}{\rm m_\odot}\frac{\rm L_\odot}{\rm L_*}\left(\frac{\rm T_{eff*}}{\rm T_{eff\odot}}\right)^4 . \tag{1}$$

Table 3 contains the obtained values along with probable errors. The standard deviations of the three criteria are 0.05 dex for ζ^1 Ret and 0.04 dex for ζ^2 Ret.

3.1.3. Microturbulence velocity

The procedure used to derive the microturbulence velocity is very similar to the one we used to derive the excitation temperature. We plot an iron abundance vs. equivalent width graph for all Fe I lines and fit a straight line. If the angular coeficient of this line is negligible (within the expected error), then we have chosen the correct microturbulence velocity. Again if the slope is significantly positive or negative we increase or decrease the microturbulence, respectively, and recalculate the iron abundancies until convergence is attained.

A probable error of 0.19 km s^{-1} for ζ^1 Ret and 0.14 km s^{-1} for ζ^2 Ret was estimated for the microturbulence velocity by changing this parameter until the angular coeficient of the linear fit equaled the error of its determination.

The adopted stellar parameters for ζ^1 and ζ^2 Ret are listed in Table 4.

3.2. Element abundances

The abundances of iron, calculated from the Fe I and Fe II lines, were obtained during the atmospheric parameters determination procedure. For ζ^1 Ret we measured 25 Fe I lines and 3 Fe II lines. For ζ^2 Ret we measured 29 Fe I lines and 4 Fe II lines. Here we have to call attention to the fact that our method of determining the temperatures by excitation equilibrium and $\rm H_\alpha$ and $\rm H_\beta$ profile fitting, the surface gravities by ionization equilibrium and the Fe abundances is completely iterative in the sense that a change in one of these parameters makes it necessary to recalculate the other ones, until all values obtained are entirely consistent with one another. Chemical abundances were calculated for Al I, Ce II, Cr I, Ni I, Si I, Ti I, Ti II and V I the same way that iron abundances were, i.e., line by line (using the adopted atmospheric parameters previously described). Since the analysis was a differential one, the abundances were derived relatively to the Sun and given in the usual notation [element/H].

Both stars were found to be a little metal deficient ([Fe/H] = -0.22). To estimate the internal probable errors of iron-relative abundances we analysed the influence of the uncertainties in the adopted atmospheric parameters and also the equivalent width measuring error according to the following procedure:

i) We recalculated [element/Fe] for all studied elements with the atmospheric parameters added to their probable errors. The effective temperature, surface gravity, microturbulence velocity and metallicity were changed one by one, independently, while the other parameters remained constant.

ii) To determine the influence of dispersion on the equivalent widths we once again compared our solar equivalent widths with those of the Kurucz solar atlas (which we supposed to be completely free of dispersion).
We plotted a ($\rm W_{atlas}$ - $\rm W_{sky}$)/$\rm W_{atlas}$ vs. $\rm W_{atlas}$ graph, whose ordinate gives the percentage error of the measurements made on the sky spectra. The weaker lines ($\rm W < 30$ mÅ) present a 7.0% dispersion,while lines stronger than 30 mÅ present a 3.7% dispersion. We increased the equivalent widths of a percentage value equal to the obtained dispersions and recalculated the abundances.

Thus after the determination of the individual probable errors (due to the uncertainties of the individual parameters) we determined the *total* probable errors:

$$\sigma_{\rm total} = \sqrt{\sigma^2_{\rm T_{eff}} + \sigma^2_\xi + \sigma^2_{\rm log\ g} + \sigma^2_{\rm [Fe/H]} + \sigma^2_W} . \tag{2}$$

Table 5 contains the abundances of all analysed elements, relatively to iron. These abundances are shown on Fig. 3 (the abundance of titanium is the average of the abundances obtained through the analysis of the Ti I and Ti II lines). The error bars are the estimated probable errors. Both stars have the abundances of all elements compatible with each other and with the Sun. The abundance of Ce for ζ^1 Ret can be regarded as marginally (within 2 σ) compatible with the abundance of ζ^2 Ret. The good agreement of the abundances of ζ^1 and ζ^2 Ret strengthens the idea of a common origin for these two stars.

4. The helium abundance conundrum

In order to investigate the hypothesis, advocated by da Silva & Foy (1987), that ζ^1 and ζ^2 Ret are helium rich relative to the Sun we plotted the stars on the Gen92/93 isochrone diagrams using our adopted effective temperatures and luminosities. Since

Table 5. Chemical abundances of ζ^1 and ζ^2 Reticuli, relatively to iron. The number of lines used is given for each star.

[elem/Fe]	ζ^1 Reticuli	N	ζ^2 Reticuli	N
AlI	$+0.05 \pm 0.04$	2	-0.01 ± 0.04	2
CeII	$+0.05 \pm 0.06$	3	-0.09 ± 0.06	3
CrI	$+0.00 \pm 0.03$	3	$+0.02 \pm 0.03$	3
NiI	-0.01 ± 0.04	6	-0.03 ± 0.04	7
SiI	$+0.05 \pm 0.04$	3	$+0.04 \pm 0.05$	5
TiI	$+0.08 \pm 0.06$	3	$+0.07 \pm 0.05$	3
TiII	$+0.10 \pm 0.05$	4	$+0.03 \pm 0.05$	4
VI	$+0.06 \pm 0.05$	3	$+0.00 \pm 0.04$	5

Table 6. Kinematic data for the stars that, according to Woolley (1970), belong to the ζ Her group. Velocities in km s^{-1}.

Name	U	V	W	ϖ	e	i
β Hyi	−60.7	−46.7	−31.0	0.8684	0.1729	0.0340
ζ^1 Ret	−70.2	−47.4	+16.4	0.8601	0.2077	0.0321
ζ^2 Ret	−69.7	−46.6	+16.8	0.8605	0.2075	0.0340
1 Hya	−59.5	−48.7	−0.7	0.8385	0.2036	0.0197
Gliese 456	−56	−52	−12	0.8286	0.2127	0.0284
ζ Her	−53.1	−48.2	−24.9	0.8481	0.1914	0.0302
HD 158614	−62.0	−43.4	−21.0	0.8501	0.2062	0.0196
HD 14680	−77.7	−55.0	−23.9	0.8488	0.2128	0.0341
ϕ^2 Pav	−65.6	−47.5	−1.6	0.8687	0.1922	0.0120

References: Velocities have been kindly calculated by G. Quast (CNPq/LNA, Brazil), based on data from the Hipparcos catalogue (ESA, 1997), except for Gliese 456 (Woolley et al., 1970). The orbital parameters ϖ, e and i come from Woolley et al. (1970).

none of the Gen92/93 sets of isochrones matches exactly the metallicity of ζ^1 and ζ^2 Ret, we interpolated in metallicity to generate an apropriate set. As a result of the interpolation we displaced the Z = 0.0080 set by $\Delta\log(L/L_\odot) = -0.0840$ and $\Delta\log(T_{\rm eff}) = -0.0152$ obtaining a Z = 0.0113 set (Fig. 5).

We can see that both stars are located *above* the ZAMS and not *below* it. Our initial analysis, using van Altena et al. (1995) parallaxes, places the stars below the ZAMS, just like in da Silva & Foy (1987) (Fig. 4). But using the much more accurate parallaxes from the Hipparcos catalogue (ESA, 1997) the stars are shifted upwards, crossing the ZAMS. It is clear, then, that ζ^1 and ζ^2 Ret are not subdwarfs, and the hypothesis that they are helium rich is no longer necessary. Its charm disappeared thanks to the crude reality of Hipparcos data.

5. The ζ Herculis kinematic group

Stars tend to form in groups, but most of the clusters and associations that are the birthplace of stars end up dispersing. The most probable cause for this dispersion is an encounter of the young cluster with a massive object. As the cluster disintegrates, it must go through intermediate stages where the entire group cannot be identified anymore, yet within some region one can still find stars that are moving in nearly the same velocity, i.e. direction and speed (after the words of Soderblom & Mayor (1993)). These stars would constitute a *stellar kinematic group* (SKG). To be considered part of a SKG, stars need to have certain characteristics:

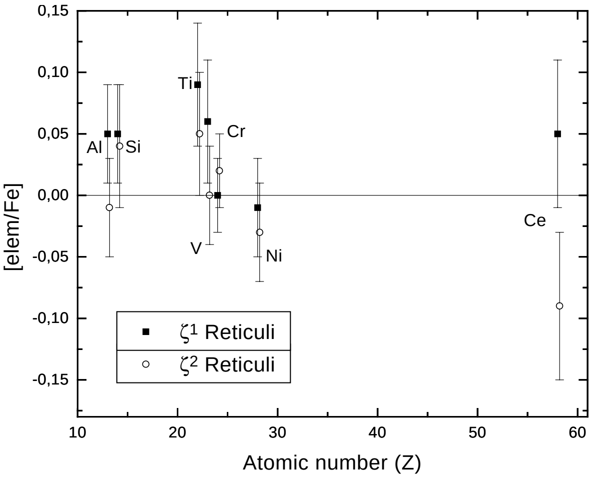

Fig. 3. The abundance pattern of ζ^1 and ζ^2 Reticuli.

i) All stars should be approximately the same age. Since they were formed in the same Giant Molecular Cloud, which disperses on a typical time scale of 0.1 Gyr, their ages shouldn't differ by more than this value.
ii) They should have the same chemical composition, which they share with the cloud from which they originated.
iii) They should be moving at the same rate in the same direction, with only minimal velocity dispersion, which reflects their spatial cohesion. It's specially important that the members of a SKG have their V velocities with very low dispersion (U, V and W are the components of a star's velocity relative to the Sun, measured in a galactic frame and positive towards the galactic centre, in the direction of galactic rotation and towards the north galactic pole respectively). The galactic forces that dissolve clusters lead to diffusion in all three directions. But motions in U and W only lead to oscillations of the stars about the mean motion of the group, whereas diffusion in V takes a star away from the group forever (Binney & Tremaine, 1987).

In Table 6 we present all stars classified as members of the ζ Her SKG according to Woolley (1970). The group presents an average velocity in the direction of galactic rotation V = 47.9 ± 3.3 km s^{-1}. This value has a standard deviation that is sufficiently low so that the group could be considered cohesive in terms of velocity. The orbital parameters mean values are $\varpi = 0.8524 \pm 0.0134$ and $e = 0.2008 \pm 0.0130$, with $i < 0.04$ for all stars (in brief, ϖ is the average distance to the galactic center, e is the orbit eccentricity and i is the orbit inclination). According to Woolley (1970) stars in a SKG must have a low orbit inclination, which all stars in Table 6 have. The low standard deviations of ϖ and e indicate a high spatial cohesion. All these stars are located less than 31 parsecs away from the Sun. We can see that, from the kinematical point of view, these stars do form a SKG. But we still have to examine if they satisfy the chemical composition and age criteria.

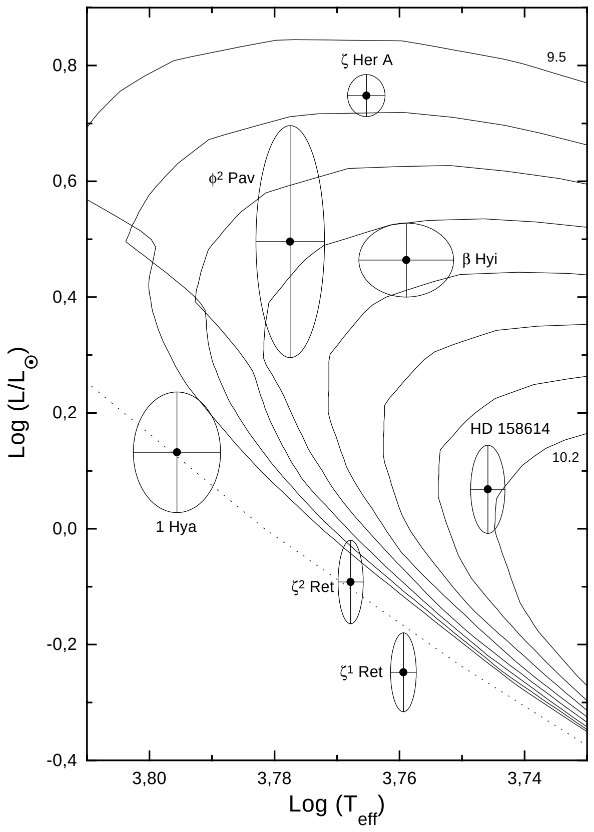

Fig. 4. H-R diagram of the probable members of the ζ Herculis group. The solid lines are the Gen92/93 isochrones for the metallicity of ζ^1 and ζ^2 Ret, varying in steps of 0.1 dex of logarithmic age (in years) from 9.5 to 10.2. The dotted line is the ZAMS. Van Altena et al. (1995) parallaxes have been used to compute the luminosities.

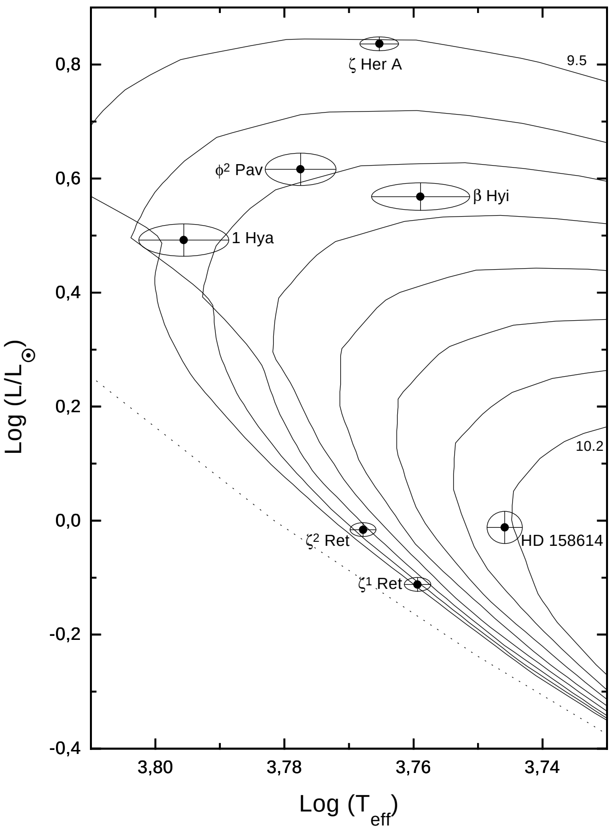

Fig. 5. The same as Fig. 4, but using parallaxes form the Hipparcos catalogue (ESA, 1997) to compute the luminosities.

We searched the literature thoroughly for detailed spectroscopic analyses of the group stars. Then we selected for each star the paper which we considered to be the most trustworthy. The selected papers were: for β Hyi, Abia et al. (1988); for ζ Her, Chmielewski et al. (1995); for HD 158614, McWilliam (1990); and for ϕ^2 Pav, Edvardsson et al. (1993). The effective temperatures and metallicities of 1 Hya and HD 14680, which have not been subjected to any spectroscopic analysis, have been determined using photometric calibrations. To determine the effective temperatures from (B$-$V) and (b$-$y) we used Porto de Mello (1996) calibrations and to have the metallicities from m_1, that of Schuster & Nissen (1989). The regression of the metallicity calibrations has a 0.16 dex dispersion and the probable error can amount to 0.20 dex. We take (B$-$V) indices from Hoffliet & Jaschek (1982) for 1 Hya and from Nicolet (1978) for HD 14680. The (b$-$y) index for HD 14680 comes from Olsen (1994a). The (b$-$y) index for 1 Hya and m_1 for both stars were taken from Olsen (1994b). Some useful parameters of the stars of Table 6 can be found on Table 7.

If we regard the ζ Her SKG as a metal deficient group then we should disregard ζ Her A (a blow of destiny!) and HD 158614 as members, because these stars have solar iron abundances. Porto de Mello & da Silva (1991), who had already analysed the group in terms of element abundances and evolutive stages, disregarded these same stars based on the determination of the stellar ages.

We also compared the abundances of elements other than iron, for the stars which had these abundances determined (Table 8). The four stars present aluminum abundances that are compatible with each other within the probable errors (ζ^2 Ret and β Hyi abundances are only marginally compatible). β Hyi and ϕ^2 Pav have barely compatible calcium abundances (within 2σ). We should keep in mind, however, that the calcium abundance of β Hyi has been determined based on the analysis of only 1 absorption line. The four stars have Si, Ti and Ni abundances that are perfectly compatible with one another. The agreement between the stars abundances reinforces the thesis that they have originated from the same interstellar cloud.

Finally, we analysed if the stars have the same age. We did so using the Gen92/93 set of isochrones corrected for the metallicity of ζ^1 and ζ^2 Ret (Fig. 5). It should be clear that the following is an imperfect analysis, because not all probable members have *exactly* the same metallicity and because of the interpolation made to construct the Z = 0.0113 set of isochrones (see Sect. 4).

ϕ^2 Pav, 1 Hya, ζ^1 and ζ^2 Ret are all compatible with the log t = 9.7 (5.0 Gyr) isochrone. β Hyi can be considered to have marginal, 2σ compatibility with the same isochrone. Because these five stars meet the characteristics required of an SKG, the

Table 7. Useful parameters for the stars that, according to Woolley (1970), belong to the ζ Her group.

Gliese Number	Name	V	Spectral Type	$\pi_{\rm van\ Altena}$ (mas)	$\rm M_{bol}$ ($\pi_{\rm van\ Altena}$)	$\pi_{\rm Hipparcos}$ (mas)	$\rm M_{bol}$ ($\pi_{\rm Hipparcos}$)	$\rm T_{eff}$ (K)	[Fe/H]
19	β Hyi	2.80	G1 IV	150.1 ± 7.2	3.59 ± 0.16	133.8 ± 0.5	3.33 ± 0.06	5740 ± 100	-0.23 ± 0.15
136	ζ^1 Ret	5.54	G3-5 V	96.6 ± 7.2	5.37 ± 0.17	82.5 ± 0.5	5.03 ± 0.03	5746 ± 27	-0.22 ± 0.05
138	ζ^2 Ret	5.24	G2 V	90.2 ± 7.3	4.98 ± 0.18	82.8 ± 0.5	4.79 ± 0.03	5859 ± 27	-0.22 ± 0.05
306	1 Hya	5.61	F5 V	55.4 ± 5.9	4.42 ± 0.26	36.8 ± 0.9	3.52 ± 0.07	6246 ± 100	-0.45 ± 0.20
456	–	11.30	dM2	55.9 ± 7.5	7.03 ± 0.29	–	–	–	–
635a	ζ Her A	2.90	F9 IV	101.7 ± 3.4	2.88 ± 0.09	92.0 ± 0.6	2.66 ± 0.03	5825 ± 40	$+0.05 \pm 0.05$
635b	ζ Her B	5.53	G7 V	101.7 ± 3.4	5.35 ± 0.13	92.0 ± 0.6	5.04 ± 0.14	5290 ± 300	–
678	HD 158614	6.05	G6 V	55.3 ± 4.4	4.58 ± 0.19	60.8 ± 1.4	4.78 ± 0.07	5570 ± 35	-0.05
9079	HD 14680	8.81	K2-3 V	42.3 ± 9.7	6.50 ± 0.46	32.5 ± 1.1	5.94 ± 0.08	4944 ± 100	-0.24 ± 0.20
9710	ϕ^2 Pav	5.12	F7 V	47.3 ± 10.1	3.51 ± 0.50	41.3 ± 0.7	3.21 ± 0.07	5991 ± 75	-0.44 ± 0.10

References: Visual magnitudes come from Hoffleit & Jaschek (1982), except for GL 456 (van Altena et al., 1995) and HD 14680 (Olsen, 1994a). Spectral types are from the Michigan Catalogue of Spectral Types (Houk & Cowley, 1975; Houk, 1982; Houk & Swift, 1999), except for ζ Her A and B (Hoffleit & Jaschek, 1982), and GL 456 (van Altena et al., 1995). Parallaxes are from van Altena et al. (1995), and from the Hipparcos catalogue (ESA, 1997). For bolometric magnitudes, effective temperatures and metallicities, see text.

existence of a group is confirmed. However, ζ Herculis itself appears not to be a member, and so we suggest that the group's name be ζ Reticuli. So, when we talk about ζ Ret SKG from now on, we will be refering to these five stars.

Another way to estimate stellar ages is through the analysis of the "chromospheric age". Young stars present generally very high levels of chromospheric activity, linked to high rotation, and these decay monotonically with time owing to magnetic braking that transfers angular momentum to the stellar wind. The traditional spectroscopic diagnostics of this activity is the core emission of very strong lines, the prototype being the Ca II H and K lines (Pasquini, 1992). These core emission equivalent widths allow an estimate of the chromospheric flux and the age through a flux -age relation. ζ^1 Ret presents an easily detectable emission at the Ca II K line core (Fig. 6), much stronger than the solar one, indicating stellar youth. ζ^2 Ret presents a much smaller emission. This is baffling for stars of equal age, very much alike, with similar luminosities and temperatures, and therefore similar masses. One conceivable explanation to this discrepancy is the possibility that ζ^1 Ret is a close binary. This possibility was already examined by da Silva & Foy (1987), with the conclusion that this is highly improbable. This result could be recently confirmed on the basis of the radial velocity monitoring of ζ^1 and ζ^2 Ret by Endl, Kürster and Els (2000). Their analysis was accomplished using a total of 14 CAT/CES spectra distributed in 185 days, for ζ^1 Ret, and 58 spectra distributed in 1977 days, for ζ^2 Ret. The r.m.s. dispersion of the radial velocities of these objects are 21.8 m s^{-1} and 17.7 m s^{-1} for ζ^1 and ζ^2 Ret, respectively, showing no hint of stellar or substellar companions. Therefore, ζ^1 and ζ^2 Ret seem to have followed different histories in their decreasing levels of chromospheric activity.

We estimated chromospheric ages for ζ^1 and ζ^2 Ret using the Ca II H and K chromospheric fluxes from Pasquini (1992) and the following flux-age relation (Soderblom et al., 1991)

$$\log \mathrm{t(years)} = (-1.50 \pm 0.03) \log \mathrm{R'}_{\mathrm{HK}} + (2.25 \pm 0.12)\,, \quad (3)$$

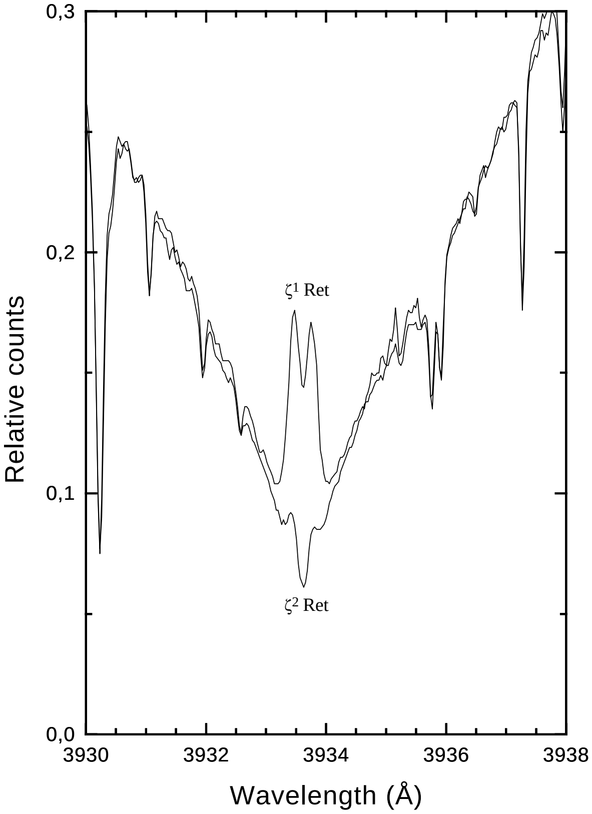

Fig. 6. Ca II K profiles of ζ^1 and ζ^2 Reticuli.

and obtained t(ζ^1 Ret) = $1.8^{+1.5}_{-0.8}$ Gyr and t(ζ^2 Ret) = $6.5^{+5.6}_{-3.0}$ Gyr. This last estimate is in reasonable agreement with the general isochronal age of 5.0 Gyr for the group. We could not find Ca II H and K published fluxes for the other group stars. Such flux-age relation analysis provides the marginal possibility of a common age (t $\sim$ 3.4 Gyr) for the ζ Ret stars, but only in view of the rather large errors involved.

Table 8. Comparison between spectroscopically determined abundances for probable ζ Her SKG members. The number of lines used is given for each star.

Star	[Al/Fe]	N	[Ca/Fe]	N	[Si/Fe]	N	[Ti/Fe]	N	[Ni/Fe]	N
ζ^1 Ret	$+0.05 \pm 0.04$	2	–	–	$+0.05 \pm 0.04$	3	$+0.09 \pm 0.06$	7	-0.01 ± 0.04	6
ζ^2 Ret	-0.01 ± 0.04	2	–	–	$+0.04 \pm 0.05$	5	$+0.05 \pm 0.05$	7	-0.03 ± 0.04	7
β Hyi	$+0.15 \pm 0.10$	2	$+0.22 \pm 0.10$	1	$+0.11 \pm 0.10$	1	–		-0.01 ± 0.10	3
ϕ^2 Pav	$+0.07 \pm 0.10$	2	$+0.03 \pm 0.10$	4	$+0.07 \pm 0.10$	8	$+0.08 \pm 0.10$	4	$+0.01 \pm 0.10$	20

Another common diagnostic of chromospheric flux is H_α (Pasquini & Pallavicini, 1991). It is a less sensitive diagnostic in the sense that the photospheric contribution is higher, but to its advantage is the fact that it is easily observable in cool stars. Our H_α observations of ζ^1 and ζ^2 Ret were discussed in Sect. 2. During the same runs we have also secured spectra of the Sun (moon) and of the ζ Ret SKG members β Hyi and ϕ^2 Pav. These four stars are the ones, along with 1 Hya, presenting a high kinematical and chemical identity, and it should be very interesting to determine if their chromospheric flux levels are compatible with a common age. During 1994 and 1995 the Sun was between the 1991 maximum and the 1997 minimum, and our solar spectra can be regarded as that of an average activity Sun. The subtraction of the solar spectra from the stellar spectra, for these very solar-like stars, should leave essentially the chromospheric component of the line core flux, which defines a small peak of excess or missing flux with respect to the Sun. All four objects present some slight additional filling with respect to the Sun, and therefore could be regarded as slightly younger. There is however some spread in their fluxes, ϕ^2 Pav being in fact the one with the strongest chromospheric component, and ζ^1 Ret presenting more H_α filling than ζ^2 Ret. It is not entirely clear if such differences are significant as they are not too far above the estimated error level. Such spread in their chromospheric H_α fluxes could be partly explained by out of phase stellar cycles, although it remains difficult to explain the appreciably more intense emission in ζ^1 Ret and ϕ^2 Pav by intercycle variation alone. These stars have about the solar age and the peak-to-peak amplitude of their H_α central depth variation should not much exceed the solar one, 0.5% (Livingston et al., 1998). The peak-to-peak total difference in their central depths reaches 25%, mostly due to the higher filling of ζ^1 Ret, the estimated uncertainty being about 5%. We are probably witnessing a true spread in chromospheric flux owing to different histories of decreasing activity levels. Such SKGs might be interesting laboratories in which to test theories of angular momentum transfer due to magnetic braking in the early stellar evolutionary stages.

Another possible test of a common age for the ζ Ret SKG stars is the abundance of Li. While the chemical evolution of Li in the Galaxy and its connection to stellar evolution remains a highly controversial subject, it is well known that young stars present a high ("cosmic") initial abundance of Li, which can be depleted with varying degrees of efficiency during stellar evolution. In this issue the ζ Ret SKG is also interesting: ϕ^2 Pav and β Hyi are both subgiants with high Li content, respectively log N(Li) = 2.5 (Soderblom, 1985) and log N(Li) = 2.4 (Dravins et al., 1993), about 10 times solar (in the usual scale log N(H) = 12.00). On the other hand, both ζ^1 Ret and ζ^2 Ret have depleted their original Li to a higher degree than the Sun, their abundances being estimated at log N(Li) $\leq$ 0.90 (Pasquini et al., 1994). One possible explanation put forward for such Li rich subgiants is the "ressurgence" scenario (Dravins et al., 1993), in which the subgiant star dredges up to the surface Li that has been preserved below the convectively unstable surface layers, or else by the fact that these stars have maintained their Li abundance owing to low levels of depletion while on the main sequence (Randich et al., 1999). Two groups might be distinguished in the case of the ζ Ret SKG: the ζ Ret pair of near solar mass stars with highly depleted Li, and ϕ^2 Pav and β Hyi, with $\sim$ 1.10 solar masses, already subgiants with enhanced lithium. Our current understanding does not preclude a common age for these four stars as judged by their Li abundances alone.

It would clearly be very interesting to perform a complete detailed analysis of these four objects plus the probable ζ Reticuli SKG member 1 Hya. Their similar Fe abundances were used as a criterion in favor of the existence of the ζ Ret SKG, but a comprehensive determination of the abundance distribution of other elements, with different nucleosynthetic origins, with respect to Fe have not yet been determined with sufficient accuracy to allow their putative chemical identity to be verified. Also, a comprehensive analysis of their Ca II H and K chromospheric fluxes, tied to other indicators such as the infrared Ca II triplet lines, would be useful in constraining their chromospheric activity level, allowing a further check of the group age. The dispersion of the H_α chromospheric fluxes suggests that the ζ Reticuli SKG, and other similar groups, may serve as interesting laboratories to test how stars with similar ages experience different histories of chromospheric activity decay with time.

6. Conclusions

Highly accurate atmospheric parameters and chemical compositions have been determined for the solar-type stars ζ^1 and ζ^2 Reticuli. The effective temperatures were obtained using 4 different criteria: excitation equilibrium, photometric calibration of 5 color indices and fitting of H_α and H_β profiles. Surface gravities were determined using the ionization equilibrium and also calculated using the obtained stellar effective temperatures, luminosities and masses (the masses being estimated with a mass-luminosity relation and evolutionary trajectories). Metalicities were determined through the analysis of Fe I and

Fe II lines. Both stars were found to be slightly metal deficient ([Fe/H] = -0.22 ± 0.05).

The problem of a possible high helium abundance of the stars disapeared, thanks to the highly accurate data used in this analysis. We do not need the high He abundance hypothesis any more. In fact, just the opposite may be true: as ζ^1 and ζ^2 Ret are metal deficient, they should also be He deficient (Perrin et al., 1977).

Common kinematical parameters, element abundances and ages of ϕ^2 Pav, β Hyi, 1 Hya, ζ^1 and ζ^2 Ret confirm the existence of a metal deficient SKG. As ζ Her A does not belong to this group, it should not be called ζ Herculis anymore. We propose it be called ζ Ret SKG. Chromospheric activity data of the group members does not preclude a common age for the group but hints at a possible real dispersion in activity levels that is evidence of possible different histories of magnetic braking for these stars.

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