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Probable nonradial *g*-mode pulsation in early A-type stars[★]

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ABSTRACT

Aims. Asteroseismology of early A-type stars could be a new tool to test stellar convection theories.
Methods. A survey for line profile variability in early A-type stars has been performed in order to detect nonradial pulsation signatures.
Results. The star HR 6139, with spectral type A2V and estimated $T_{\rm eff} = 8800$ K, shows evident line profile variations that can be explained by oscillations in prograde *g*-modes. This feature and the known photometric variability are similar to those observed in the Slowly Pulsating B-type stars. However HR 6139 is much cooler than the cool border of the instability strip of such variables, and it is hotter than the blue edge of the δ Scuti instability strip. There are indications of a tiny variability also in other four objects, whose nature is not yet clear.

Key words. stars: oscillations – stars: variables: general

1. Introduction

The modelling of convection is one of the main astrophysical problems that are to be solved, and the proposed theories cannot be adequately tested since an effective experimental tool is still lacking. The new satellite COROT (Baglin et al. 2001), that will be launched in 2006, is intended to probe stellar interiors by means of asteroseismology, though only the modes with lowest degree ℓ can be detected photometrically. Asteroseismology promises to be a very effective tool to obtain detailed and independent information on the size of convective zones and on the extent of overshooting. An analysis of solar-like *p*-modes of main sequence models shows that, whereas the seismic signatures of the convective envelope are very small (e.g. Ballot et al. 2004), larger effects are predicted for convective cores of intermediate-mass stars (e.g. Roxburgh & Vorontsov 1994; Miglio & Antonello 2004). As shown by Straka et al. (2005), in addition to pressure modes, further and more detailed information on the stellar core can be gathered from the periods of gravity modes, which are direct probes of the deep stellar interior. It is therefore important to study the seismology of early-type stars and, in particular, to detect *g*-mode oscillations.

Known *g*-mode pulsators close to the main sequence include the Slowly Pulsating B-type stars (SPB) and the γ Dor (F-type) stars. Pamyatnykh (1999) discussed the pulsational domains in the upper main sequence, and excluded the presence of pulsators in the spectral range B8-A2, i.e. later than the SPB domain and earlier than the δ Scuti star domain; however, he remarked that stellar rotation and metallicity can have an effect on such domains. Townsend (2005a,b) also discussed some effective mechanisms that can change the extent of the theoretical instability strip of SPB stars.

The finding from theoretical three-dimensional simulations of persisting, global *g*-mode oscillations (resonances) induced by the convection coupled to rotation in the early A-type star cores (Browning et al. 2004) opens a new possibility. These modes with low ℓ should have a frequency of the order of or less than two times the rotation frequency. Browning et al. (2004), however, give warning on the simplifications adopted in their study, and moreover it is not clear whether such modes can propagate in the envelope. On the other hand, Koen (2001), from the analysis of the variable stars in the HIPPARCOS catalog, has suggested the existence of a possible group of slowly pulsating stars among the early A-type stars.

In the present paper we report the main results of an exploratory program dedicated to the detection of nonradial mode signatures in moderately rotating early A-type stars.

2. Observations and data analysis

The observations were performed with the FEROS spectrograph attached to the 2.2 m telescope at ESO-La Silla, with resolution 48 000 and spectral range λ350–930 nm, during

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[★] Based on observations collected at ESO-La Silla; program 75.D-0342.

Table 1. Target stars.

Name (HR)	V	Sp.T.	# spectr.	S/N	$v \sin i$	s.d. ratio	t−test	result
5028	2.75	A2V	26	5800	88	1.310	5.40	var?
5332	5.53	A1V	23	2100	111	1.015	0.15	const.
5670	4.07	A3V	23	4300	69	1.099	1.59	const.
5859	5.58	A0V	14	4100	69	1.384	4.72	var?
5905	5.76	A3V	24	4000	89	1.204	3.59	var?
5925	5.12	A3V	11	5000	53	2.025	7.34	spectr. bin.
6139	6.04	A2V	37	2900	94	5.540	19.53	*g*-modes
6681	5.93	A0V	17	3400	60	16.333	8.06	spectr. bin.
7950	3.77	A1V	10	5400	112	1.219	2.82	var?

a three-night run (May, 25–29, 2005). Other spectra were also gathered in June, 18–21, 2005, with the same instrumentation. The targets were selected among the brightest A0–A3 type stars, with projected rotational velocities between 50 and 100 km s^{-1}; the known binaries and chemically peculiar stars were excluded. The brightness requirement is due to the very high S/N ratio needed. The stars were observed cyclically during all the nights; the typical separation between the spectra of the same star was about one hour. The exposure times were estimated in such a way to get $S/N \gtrsim 300$ in the best spectral range. The nine stars are listed in Table 1, along with their apparent magnitude, the spectral type, the number of spectrograms, the S/N ratio, the rotational velocity estimated by us, the ratio of the average standard deviations in the line region and in the continuum region with the corresponding t-test (discussed below), and the results of the survey for variability. In the literature the MK classification of the nine stars is rather consistent, and there are no significant discrepancies or indications of peculiarities. Furthermore, for two stars, HR 5670 and HR 7950, there are indications of normal abundances (Andrievsky et al. 2002; Kocer et al. 2003).

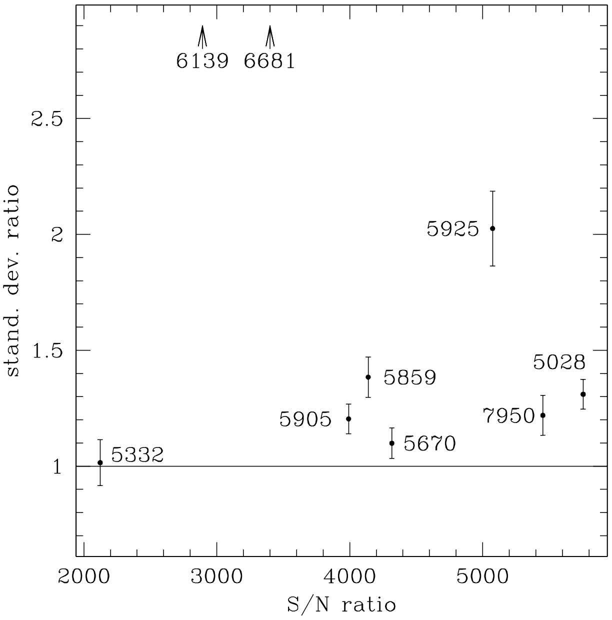

Fig. 1. Ratio between the average standard deviations in the line region and in the continuum region, against the S/N ratio.

The spectrograms were reduced and normalized to the continuum level by means of a pipeline developed by us. We constructed a mean photospheric profile, using the information contained in all photospheric lines present in the spectrum. The Least Squares Deconvolution (LSD) method developed by Donati et al. (1997) consists of deconvolving the observed spectrum with a mask function including all expected spectral lines with their expected depth, as calculated from a model atmosphere, with the exclusion of the strongest lines whose profiles are dominated by other broadening mechanisms than the rotation. This allows to construct a mean line profile combining the information contained in thousands of lines, and therefore with a very high S/N ratio, typically of several thousands. The input parameters for the model atmospheres of our stars were estimated using the *uvbyβ* and Geneva photometry data taken from SIMBAD database, and with the calibrations of Napiwotzki et al. (1993) and Kunzli et al. (1997). As a by-product we estimated the $v\sin i$ values on the basis of the position of the first zeros of the Fourier transform of the mean line profile (e.g. Royer et al. 2002). Our $v \sin i$ values are not very different from those previously known, except for the star HR 5925 (resolved spectroscopic binary). The uncertainty in the $v \sin i$ values reported in Table 1 is of the order of 1–2 km s^{-1}.

We computed the average value of the mean line profile of all the spectra of a star and the standard deviation in each wavelength bin. The mean standard deviation in the continuum region allows us to estimate the mean S/N ratios of the individual mean profiles. In our cases we estimated S/N values between 2100 and 5800. The comparison of the standard deviation values inside and outisde the line profile allows us to detect the possible variations of the line profile shape. From a visual examination of these curves, three stars showed evident variability: HR 6139, HR 5925 and HR 6681. However, in order to give a quantitative estimate of the variability, two average standard deviations were computed: one in the continuum region and the other in the line region. A Student's t test was performed in order to evaluate whether these two values are significantly different: if $t > 2.6$ in our data the significance level is less than 0.01, i.e. the difference is highly significant. The results are reported in Table 1, and the ratios of the two standard deviations are shown in Fig. 1. The error bars are actually overestimated, since they reflect the nonuniform variability within

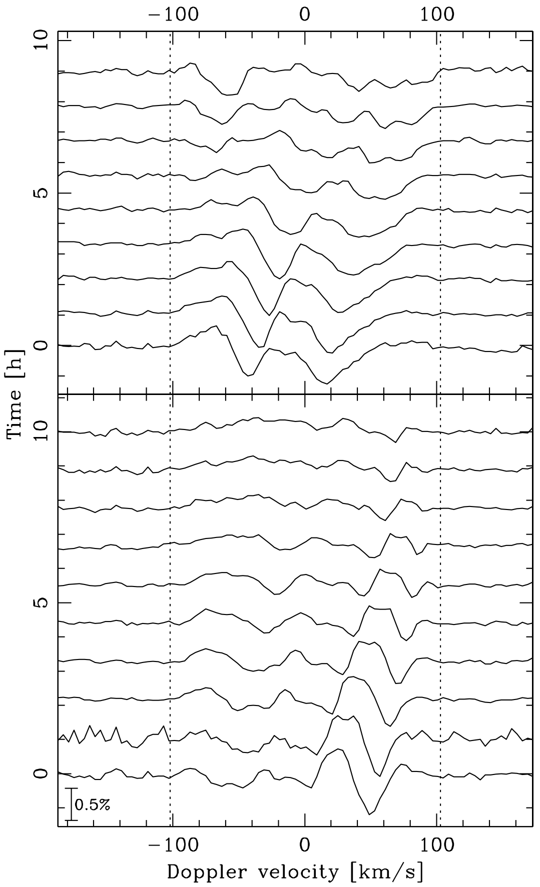

Fig. 2. Variations of the mean line profile of HR 6139 during two consecutive nights; the average mean line profile has been subtracted. The dashed lines correspond to the borders of the average mean line. The progression of the shape of the profile suggests the presence of nonradial modes with a variability timescale of many hours. The bar in the lower left corner indicates an amplitude of 0.5% of the continuum flux.

the line profile. The most extreme case is the binary HR 6681, which has very large variations confined just in the line wings.

3. Results and discussion

In this paper we present the relevant results for our scientific motivation, that is those for HR 6139 and HR 5028. A more detailed presentation and discussion of the results for all the stars along with comparisons with possible models will be reported in another paper. Here we just mention that the variability of HR 5925 and HR 6681 can be easily explained by their (previously unknown) spectroscopic binariety.

Figure 2 shows the line profile variations of HR 6139 during two consecutive nights. The presence of nonradial oscillations propagating in the sense of the stellar rotation is evident. There is a progression of the complex shape of the mean line profile, and the timescale of the variability suggested by this progression is of many hours. Figure 3 shows the "global least-squares power spectrum", that is the result of the pixel-by-pixel frequency analysis (Mantegazza 2000). This spectrum takes into account the information about the variability of the whole line profile. It shows that the spectral power of the line profile variations is concentrated at frequencies considerably lower than 5 c/d, which is the estimated value of the fundamental radial mode frequency of HR 6139. Therefore the line profile variation is probably due to prograde g-modes. The spectral window is too much entangled to allow the discrimination of the individual modes. HR 6139 is a known small amplitude photometric variable ($\sim$0.02 mag), and Koen (2001), using HIPPARCOS data, detected two periods, 0.38 and 0.64 c/d. However, the two photometric periods are not sufficient to explain all the line profile variations. The estimated $T_{\rm eff}$ from $uvby\beta$ and Geneva photometry is about 8800 K, and the absolute magnitude derived from HIPPARCOS parallax, with correction for a small reddening $E(b-y) = 0.006$, is $M_V = -0.30 \pm 0.21$; there is no evidence of binariety, and HR 6139 looks like a normal single star. On the whole, its variability reminds of that of the SPB stars (e.g. DeCat et al. 2005; Aerts & Kolenberg 2005). However the star is much cooler than the cool border of the SPB star instability strip predicted by the models, even if we take into account the proposed mechanisms that can extend the strip. On the other hand, it is hotter than the blue border of the δ Scuti star instability strip. Therefore HR 6139 is apparently challenging the present theoretical models.

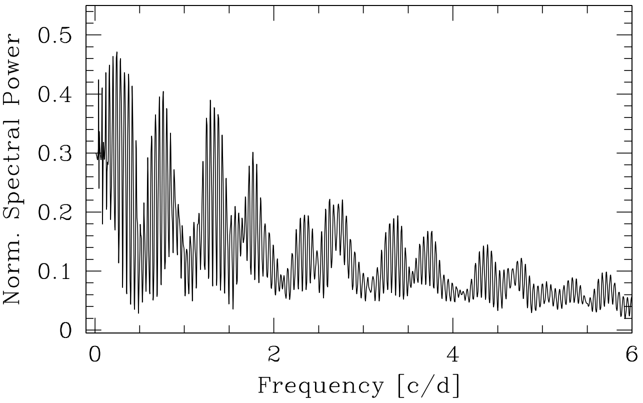

Fig. 3. Global least-squares power spectrum (Mantegazza 2000) of the mean line profile time series of HR 6139. This spectrum takes into account the information about the variability of the whole mean line profile. One should note the large power at low frequencies.

It is too early to identify HR 6139 as a prototype star for the mechanism found by Browning et al. (2004), and we suspect that such a mechanism, if present, should give smaller effects. In this respect, the result for HR 5028 shown in Fig. 4 could be of some interest. In the lower panel of this figure we compare the behaviour of the standard deviations of the velocity bin timeseries in the line profile with those in the adjacent continuum regions. The dashed horizontal line is the average standard deviation in the continuum, and it can be interpreted as the noise level. The standard deviations of the timeseries of the line profile bins are slightly larger. As a reference, in the upper panel we show the average line profile. In Fig. 5 it is shown for comparison purposes the profile of the constant star HR 5670; in this case there are no differences between the line profile and the adjacent continuum. We are not able to offer an

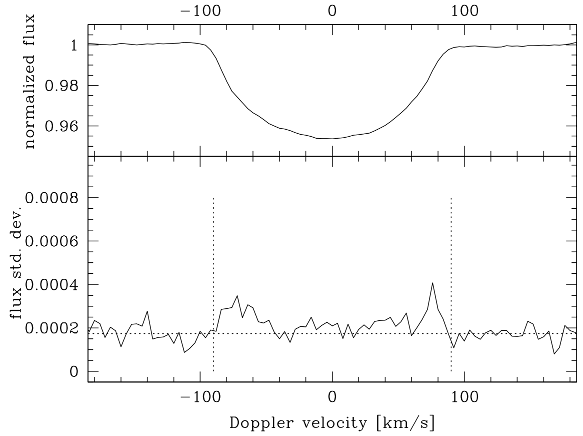

Fig. 4. *Upper panel*: average line profile of HR 5028. *Lower panel*: the tiny variability indicated by the relatively large standard deviation from the mean of the average line in comparison with the relatively small standard deviation of the adjacent continuum. The horizontal dashed line represents the mean level of the standard deviation of the continuum, which can be interpreted as noise level.

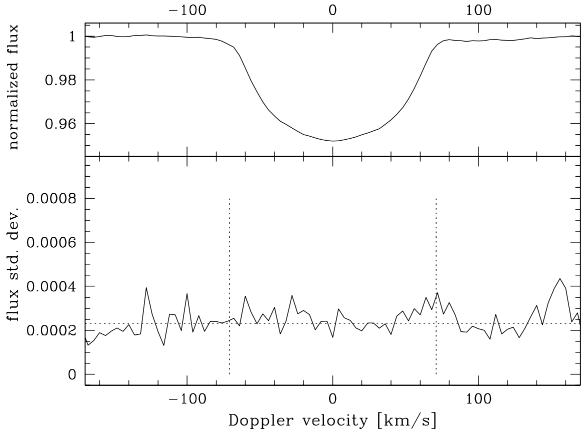

Fig. 5. Average line profile of HR 5670. In this case the standard deviation from the mean of the average line is not different from that of the mean level continuum (dashed line).

explanation of the *tiny* variability of the line profile bins with respect to the continuum of the stars such as HR 5028, and for the present we cannot ascribe it to possible very small oscillations. A more solid database is needed to address this issue adequately.

We intend to continue the survey in order to find other cases of g-mode (and possible p-mode) pulsators among early-A type stars. In the past fifty years there were several claims of (or attempts to verify) the existence of pulsating stars in this narrow spectral region, hence it is mandatory to increase the observational evidences before attempting to define a new possible class.

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