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FN Aquilae – an unusual Cepheid with anomalous CNO abundances*

I. A. Usenko[1,3], V. V. Kovtyukh[1,3], and V. G. Klochkova[2,4]

[1] Astronomical Observatory of Odessa State University, Odessa 65014, Ukraine
e-mail: `val@deneb.odessa.ua`
[2] Special Astrophysical Observatory, Russian Academy of Sciences, Nizhny Arkhyz, Stavropol Territory 369167, Russia
e-mail: `valenta@sao.ru`
[3] Isaac Newton Institute of Chile, Odessa Branch, Ukraine
[4] Isaac Newton Institute of Chile, SAO RAS Branch, Russia

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Abstract. Spectroscopic analysis of the classical Cepheid FN Aql from three high–resolution CCD spectra near minimum and maximum light gives the following results: 1) Mean $T_{\rm eff}$ = 5483 K; log g = 1.25 and $V_{\rm t}$ = 4.0 km s^{-1}; 2) Metallicities derived for each phase are consistent with each other and close to the solar value; 3) The Cepheid is crossing the instability strip for at least the third time. 4) It has anomalously low carbon ([C/H] = −0.93 dex) and nitrogen ([N/H] = +0.09 dex) abundances, which is unusual for a Cepheid not crossing the instability strip for the first time. Since FN Aql is an IRAS object and candidate protoplanetary nebulae according to Volk & Kwok (1989), we assume that the star's peculiarities are caused either by envelope loss after the second dredge-up or that it is an unusual Cepheid for which existing nucleosynthesis and mixing models are unable to reproduce the CNO abundance pattern.

Key words. stars: abundances – stars: variables: Cepheids

1. Introduction

Classical Cepheids (DCEP) are recognized to be intermediate mass F–G supergiants that are crossing the Cepheid instability strip (hereafter CIS) during specific evolutional phases. Evolving off the main sequence they move through the CIS for the first time, retaining carbon and nitrogen surface abundances close to the solar value, right up to the red giant region. There the ignition of helium at the core takes place, bringing substantial changes in the interior structure – the so-called "first dredge-up". As a result of such changes there is an incomplete transfer to the stellar surface of CNO-cycle processed material. Once core material is mixed with atmospheric gas, the original atmospheric CNO abundances undergo the following changes: carbon becomes deficient and nitrogen overabundant relative to their initial values, while the oxygen abundance remains practically unchanged. The process was illustrated in papers by Luck (1978), Luck & Lambert (1981, 1985, 1992), Luck (1994), and Luck & Wepfer (1995). The general conclusion of all these papers is that F–G supergiants with masses of 5−12 $M_\odot$ are carbon deficient at about [C/H] = −0.3 dex and nitrogen overabundant at about [N/H] = +0.3 dex. The results were later confirmed and improved upon by Andrievsky et al. (1996), Kovtyukh et al. (1996), Andrievsky & Kovtyukh (1996), Kovtyukh & Andrievsky (1999), and Usenko et al. (2001) for DCEP, small-amplitude Cepheids (DCEPS), and non-variable supergiants (NVS): [C/H] = −0.15 to −0.3 dex and [N/H] = +0.3 to +0.5 dex. Such results appear to be typical of the overwhelming majority of investigated F–G supergiants in our Galaxy.

2. Cepheid FN Aql

The classical Cepheid FN Aql, with a pulsational period of $9\overset{\rm d}{.}48$ according to the GCVS (Kholopov et al. 1985), was classified as DCEPS because of its sinusoidal light curve. However, Berdnikov & Pastukhova (1994) have demonstrated that within the scatter originating from observational error (for the most part visual and photographic observations), two humps can be distinguished near the crest of the light curve. Those two humps are typical features of classical Cepheids (DCEP) with pulsational

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Send offprint requests to: I. A. Usenko,
e-mail: `igus@deneb.odessa.ua`

[*] Based on spectra collected with the 6 m telescope SAO RAS.

Table 1. Observational data.

Spectrum No.	HJD 2 440 000+	Phase (*)	Spectral region (Å)	Number of orders	Exposure (min)
s03108	8850.4063	0.464	5000–7200	30	20
s06201	9173.3528	0.525	5550–8800	32	60
s11406	9887.4701	0.841	4700–6950	32	20

*Phase values according to Berdnikov & Pastukhova (1994).

periods of 9^{d} to 10^{d}. FN Aql is therefore *a typical* DCEP type variable. Such a conclusion is confirmed by the star's estimated amplitude of $0\overset{\mathrm{m}}{.}57$ in V according to Fernie et al. (1995) (amplitudes in V do not exceed $0\overset{\mathrm{m}}{.}5$ for DCEPS).

Furthermore, FN Aql is also suspected to be a binary. Its BVI and $VBLUW$ photometric data (Dean 1977; Pel 1978) provide some evidence that FN Aql has a blue companion. Szabados (1988), using O−C diagram data, estimated its orbital period to be 15.43 yr with $a \sin i = 14.79 \pm 3.4$ AU. That implies a mass function for the system of $(M_1{+}M_2) \sin^3 i = 13.6 \pm 10.4\ M_{\odot}$. Usenko (1990), using the position of FN Aql in the two-colour $(U-B) \sim (B-V)$ diagram for unseparated binaries, estimated the companion's spectral type to be B8 V. At the same time, Evans et al. (1990), using *IUE* satellite spectra, did not detect any flux from the suspected companion in the spectral range from 2500 Å to 2600 Å. They concluded that if FN Aql has a companion, its spectral type must be cooler than *A*1 *V*. The evolutionary masses of the Cepheid and its companion were estimated to be about 7 $M_{\odot}$ and 2.2 $M_{\odot}$, respectively.

Berdnikov & Pastukhova (1994), using Herzsprung's method for the reduction of existing observations, did not detect any obvious periodic variations in the O−C diagram. Therefore, the question of FN Aql's possible duplicity is still open.

With regard to evolutionary changes in pulsational period, Berdnikov & Pastukhova (1994) have noted evidence for a small increase in pulsation period from the O−C diagram, while Turner (1998) found a small negative period change. Both estimates suggest that any period changes are negligibly small, which makes it difficult to make any definite conclusions about FN Aql's period changes.

According to the GCVS, the spectral type of FN Aql varies between F8 and G2, and its mean colour index is fairly small: $(B-V)_0 = 0\overset{\mathrm{m}}{.}704$ (Fernie et al. 1995). Both results suggest that the Cepheid lies near the red edge of the CIS. In addition, FN Aql is a source in the IRAS Low Resolution Spectral Catalog (object IRAS 19102 +0329), and Volk & Kwok (1989) selected it as a candidate protoplanetary nebula (PPN).

While all photographic, visual, and photoelectric observations of FN Aql cover an interval of more than 70 years, there are few spectroscopic studies of this Cepheid (except for sporadic radial velocity observations).

Table 2. Atmospheric parameters of FN Aql.

Spectrum	Phase	T_{eff}	$\log g$	V_{t}
s03108	0.464	5170	1.00	3.80
s06201	0.525	5160	1.00	3.80
s11406	0.841	5740	1.50	4.20

Given the peculiarities mentioned above, it is of great interest to carry out a spectroscopic analysis of FN Aql.

3. Observations

Three high-resolution spectra of FN Aql were obtained with an échelle spectrometer LYNX (Panchuk et al. 1993) installed on the 6 m telescope of Special Astrophysical Observatory, Russian Academy of Sciences (Russia, Northern Caucasus). The resolving power is $R \sim 24\,000$ for observations with $S/N \sim 100$. Information concerning the CCD spectra of FN Aql is given in Table 1.

By means of the MIDAS software, we extracted the spectra from CCD frames, subtracted dark frames, removed cosmic ray hits, and performed a wavelength calibration. All of the equivalent widths (W_{λ} values) were measured using the DECH20 code (Galazutdinov 1992). In our analysis we did not use lines with equivalent widths greater than 150 mÅ. The internal accuracy of the equivalent widths is of the order of 5–10%, based upon a comparison of values derived from lines present in two overlapping spectral orders.

4. Atmospheric parameters

Since FN Aql is a yellow supergiant, its effective temperature at each observed phase was obtained from line depth ratios for iron peak elements using pairs of lines with different excitation potentials (Kovtyukh & Gorlova 2000), to within an accuracy of ±50–80 K. The surface gravities ($\log g$) were determined by adopting the same iron abundance from Fe I and Fe II lines, to within a mean uncertainty of ±0.15 dex. The microturbulent velocities (V_{t}) were obtained by assuming that the abundances from the Fe II lines are independent of the equivalent line widths, with a mean uncertainty of 0.25 $\mathrm{km\,s^{-1}}$. The adopted atmospheric parameters are listed in Table 2.

Table 3. Element abundances for FN Aql.

Element	s03108			s06201			s11406			Average	
	[El/H]	σ	NL	[El/H]	σ	NL	[El/H]	σ	NL	[El/H]	σ
C I	−0.80	0.06	3	−0.81	0.19	3	−1.03	0.20	7	−0.93	0.07
N I	–	–	–	+0.09	0.05	2	–	–	–	+0.09	0.05
O I	+0.19	0.28	3	+0.03	0.26	3	−0.18	0.60	5	−0.02	0.42
Na I	+0.28	0.10	3	+0.26	–	1	+0.46	0.25	4	+0.37	0.16
Mg I	+0.49	0.01	2	+0.14	0.21	5	+0.27	0.27	4	+0.25	0.20
Al I	+0.13	0.06	2	+0.34	0.12	4	+0.22	0.12	2	+0.26	0.11
Si I	+0.01	0.16	27	+0.04	0.18	20	+0.05	0.10	21	+0.03	0.15
Si II	−0.14	–	1	+0.46	–	1	−0.19	0.32	3	−0.05	0.19
S I	−0.06	0.29	5	+0.19	0.28	3	+0.01	0.20	6	+0.02	0.25
K I	+0.43	–	1	–	–	–	–	–	–	+0.43	–
Ca I	−0.09	0.26	9	+0.07	0.34	9	−0.01	0.09	7	−0.01	0.24
Sc II	−0.13	0.16	3	−0.53	0.00	1	−0.06	0.24	7	−0.12	0.20
Ti I	−0.08	0.24	53	+0.08	0.22	31	+0.17	0.21	57	+0.06	0.22
Ti II	−0.19	0.08	3	−0.13	–	1	+0.05	0.17	5	−0.05	0.12
V I	−0.13	0.17	27	−0.14	0.22	22	+0.14	0.13	23	−0.05	0.17
V II	−0.05	0.25	5	−0.08	0.13	2	−0.12	0.35	5	−0.08	0.27
Cr I	−0.11	0.21	22	+0.11	0.40	11	+0.21	0.20	38	+0.10	0.23
Cr II	−0.00	0.19	8	–	–	–	+0.07	0.12	7	+0.03	0.16
Mn I	−0.27	0.26	13	−0.66	0.05	3	−0.22	0.13	12	−0.29	0.18
Fe I	−0.02	0.15	185	−0.03	0.16	119	+0.03	0.12	176	−0.00	0.14
Fe II	−0.03	0.11	21	−0.02	0.14	15	+0.01	0.11	26	−0.01	0.12
Co I	−0.24	0.25	30	−0.04	0.43	17	+0.04	0.26	29	−0.02	0.29
Ni I	−0.15	0.25	65	−0.20	0.19	39	+0.05	0.18	77	−0.08	0.21
Cu I	−0.01	0.58	4	−0.48	0.46	2	+0.24	0.31	4	+0.00	0.45
Zn I	+0.17	–	1	−0.11	–	1	+0.02	0.44	3	+0.02	0.26
Y I	−0.17	–	1	+0.29	–	1	−0.06	–	1	+0.02	–
Y II	−0.10	0.49	7	+0.29	0.21	3	+0.07	0.25	6	+0.04	0.35
Zr II	−0.23	0.07	3	−0.33	–	1	−0.06	0.16	5	−0.15	0.11
La II	−0.00	–	1	+0.15	–	1	+0.03	0.28	4	+0.05	0.19
Ce II	−0.02	0.22	6	−0.23	–	1	−0.03	0.13	10	−0.04	0.15
Pr II	−0.37	0.41	4	–	–	–	−0.38	0.05	3	−0.37	0.26
Nd II	−0.05	0.38	13	+0.18	0.09	3	+0.09	0.17	17	+0.04	0.25
Sm II	–	–	–	–	–	–	+0.03	0.24	3	+0.03	0.24
Eu II	+0.10	0.33	2	+0.50	0.32	3	+0.09	0.01	2	+0.27	0.23
Gd II	−0.24	–	1	+0.47	–	1	+0.09	–	1	+0.11	–

NL – number of lines.

5. Chemical composition

5.1. Method of analysis

Each atmosphere model was interpolated from Kurucz's (1992) grid, and our implementation of WIDTH9 code was used for analysis. We adopted so-called "solar" $\log gf$ values (Kovtyukh & Andrievsky 1999), derived by us using unblended solar lines from the solar spectrum of Kurucz et al. (1984). The corresponding solar atmosphere model was recalculated with $V_{\rm t} = 1$ km s^{-1} from Kurucz's grid using the WIDTH9 code. Solar element abundances were taken from Grevesse et al. (1996).

5.2. Element abundances

In Table 3 we give the derived element abundances separately for each pulsational phase of FN Aql. Abundances averaged over the three phases are shown in Fig. 1.

Inspection of the data from Table 3 and Fig. 1 suggests that FN Aql has generally a solar metallicity. However,

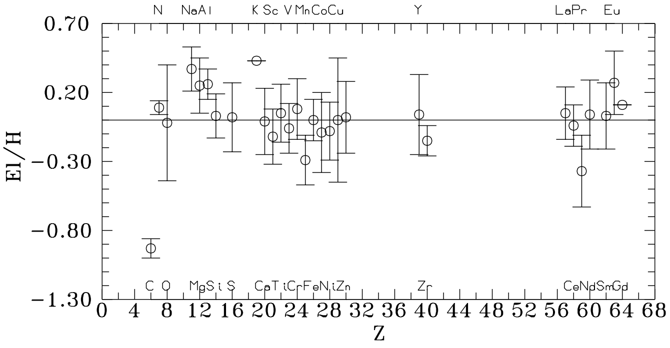

Fig. 1. Averaged elemental abundance for FN Aql.

what immediately catches the eye is an anomalously low carbon abundance relative to a nitrogen abundance that is nearly solar. It seems clear that FN Aql is crossing the CIS not for the first time, namely that it is an object in the post red supergiant evolutionary phase. Nevertheless, such a low carbon abundance (almost by an order of magnitude relative to the Sun) along with a very low nitrogen excess evidently requires another interpretation.

5.3. Luminosity, radius and mass

Since FN Aql is a post first dredge-up yellow supergiant, its evolutionary mass can be determined from the mass–luminosity relation with overshooting (Antonello & Morelli 1996):

$$\log(L/L_\odot) = 3.52\log(M/M_\odot) + 0.9. \qquad (1)$$

Using $M_V = -4\stackrel{\mathrm{m}}{.}04$ from Fernie et al. (1995) and our mean $T_{\rm eff} = 5483$ K, we obtain a luminosity of 3342 $L_\odot$, a radius of 64.3 $R_\odot$, and a value of $M_{\rm ev} = 5.6\ M_\odot$. Sachkov et al. (1998) estimated a mean radius of 68.5 $R_\odot$ for FN Aql. Its evolutionary track was interpolated from Schaller et al. (1992). On the basis of Fig. 2, FN Aql occupies a place in the HR diagram that corresponds to at least a *third* crossing of the CIS. The Schaller et al. (1992) grid of models predicts for this case [C/H] = −0.15 dex, [N/H] = +0.45 dex, and [O/H] = −0.08 dex, respectively. In our case we estimated mean values of [C/H] = −0.93 dex, [N/H] = +0.09 dex, and [O/H] = −0.02 dex. Only for oxygen is there an approximate agreement with theoretical predictions.

6. Discussion

We find that FN Aql is a Cepheid with an overall metallicity close to solar, but with a strong carbon deficit and a small nitrogen overabundance. We can say with some confidence that it has crossed the CIS more than once. However, two questions remain to be answered:

1) If FN Aql is crossing the CIS for at least the *third* time, why is there a discrepancy between the theoretically predicted and observed abundances for carbon and nitrogen?

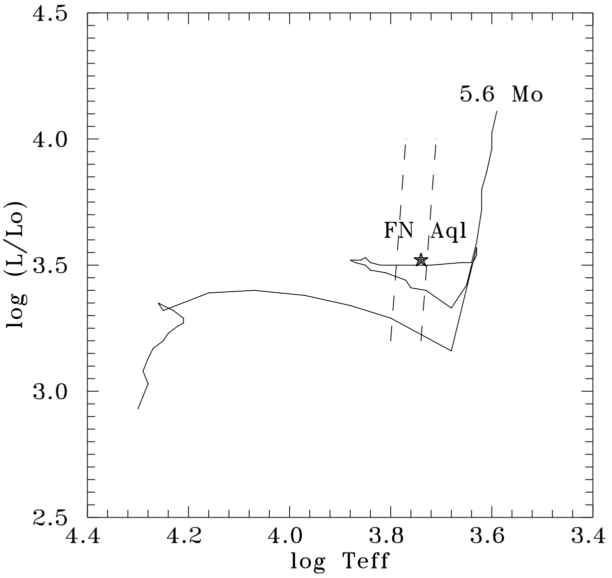

Fig. 2. The HR diagram for FN Aql. The instability strip edges for fundamental mode pulsation were derived using relations from Chiosi et al. (1992).

2) What is the physical nature of FN Aql as an IRAS object, namely what has resulted in its identification as a candidate PPN?

The following ideas are suggested to resolve the above problems:

1) The high IR brightness of FN Aql may be evidence of envelope loss. From its position in the HR diagram relative to evolutionary tracks, one might assume that FN Aql is a Cepheid that has recently passed through the *second* dredge-up stage. In that case its position must agree with a *fourth* crossing of the CIS. Unfortunately, the Schaller et al. (1992) grid of models, as well as the majority of other modern ones, do not extend to the fourth and fifth crossings of the CIS for intermediate mass stars. Therefore, the observed anomalies in CNO abundances may result simply from incompleteness in the theoretical models.

2) Apparently existing nucleosynthesis and mixing models are unable to reproduce the CNO abundance pattern of this unusual Cepheid.

In summary, we find that a new type of Cepheid has been identified whose chemical abundance pattern cannot be explained within the current theoretical framework. This unusual Cepheid, FN Aql, deserves further attention.

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