Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 20 July 2012 (MN LaTeX style file v2.2)

A CH star in the globular cluster NGC 6426

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Accepted . Received ; in original form

ABSTRACT

We report on the serendipitous discovery of a carbon star near the centre of the low-metallicity globular cluster NGC 6426. We determined its membership and chemical properties using medium-resolution spectra. The radial velocity of -159 km/s makes it a member of the cluster. We used photometric data from the literature and the COMARCS stellar atmospheric models to derive its luminosity, effective temperature, surface gravity, metallicity, and approximate C, N, and O abundance ratios. According to these properties, we suggest that this star is a genuine carbon rich low-metallicity AGB star.

Key words: Stars: carbon - globular clusters: individual: NGC 6426

1 INTRODUCTION

The role of globular clusters (GCs) in the chemical evolution of galaxies will be better understood by studying carbon stars (CSs) in the former. Only two types of CSs have abundances and kinematics typical for the Galactic halo: the giant and dwarf CH stars (McClure 1985; Green 1996). In the field most of these stars are binaries, where the primary owes its peculiar nature to mass transfer from its white-dwarf companion rather than to dredge-up from the interior (McClure & Woodsworth 1990). There is no observational evidence for the exact nature of CH stars in GCs. The chemical differences between CH stars that are intrinsic asymptotic giant branch (AGB) stars and those in binary systems are detailed by Abia et al. (2003).

Only three CH stars were found in GCs so far: two in Ω Cen, RGO55 and GRO70 (Harding 1962; Dickens 1972), and a probable one in NGC 6402 (Côté et al. 1997). The two CH stars in Ω Cen cannot be in the horizontal-branch phase (Abia et al. 2003). Both GCs are of low-metallicity, and presumably belong to the Galactic halo. Searches for CH stars in other clusters have been unsuccessful (Palmer 1980; Palmer & Wing 1982).

We report on the serendipitous discovery of a CH star in a globular cluster, and analyse its spectra to establish its properties and find clues as to its exact spectral type.

2 OBSERVATIONS AND DATA REDUCTION

The CH star is located about 24.5″ or $1.6 r_c$ south-east of the centre of NGC 6426, a low-metallicity GC in the Galactic halo. Its coordinates, obtained with HST images and in the 2MASS all-sky point source catalogue[1], are: RA(J2000)= $17^h44^m55\overset{s}{.}05$; Dec(J2000)= $+03^\circ 10\overset{'}{.}09\overset{''}{.}8$.

The star was discovered during an observing run on 10 June 2010, at the 1.93m telescope of Observatoire de Haute-Provence (OHP) aimed at obtaining integrated spectra of Galactic globular clusters with the CARELEC spectrograph (Lemaitre et al. 1990) and the grating 300 lines/mm. Two long-slit ($5.5' \times 2''$) spectra were obtained at the same position and PA=145.7°, both with 20-minute exposures and a seeing $\sim 2.5''$. The corresponding dispersion and the spectral resolution were ~ 1.78Å/pixels, and ~ 5Å, and the spectral range was $\sim 3700 - 6800$Å. Helium and Neon lamps were exposed at the beginning and the end of the night for wavelength calibration. For relative flux calibration and radial velocity calibration one flux standard HR8634 (Hamuy et al.

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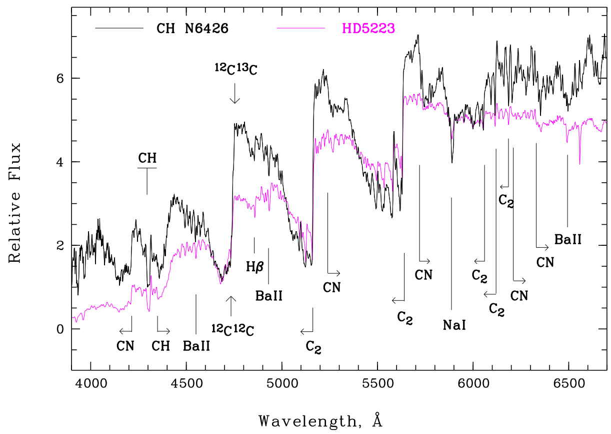

Figure 1. Spectrum of the CH star. The main spectral features are indicated. The spectrum of a classic CH star HD5223 from Goswami (2005) is shown in gray for comparison.

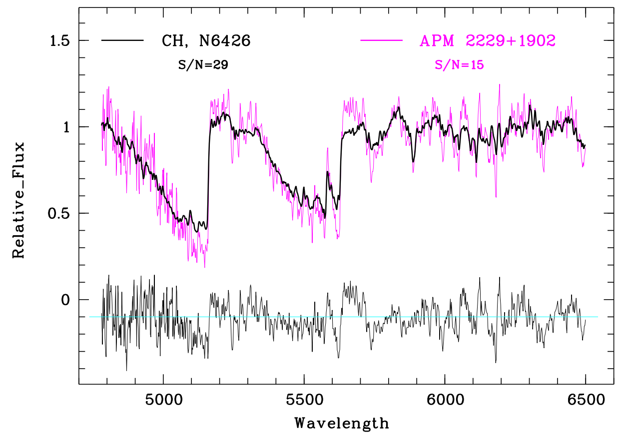

Figure 2. Radial velocity determination for the CH star using the method PPXF.

1992, 1994), two Lick standard stars (HR5933 and HR7030) from the list of Worthey et al. (1994), and an N-type CS (APM 2229+1902) from the list of Totten & Irwin (1998) were observed on the same night. The signal-to-noise per resolution element at 5000Å is S/N∼29.

In order to reach a better S/N in the blue and to benefit from a higher spectral resolution, additional long-slit spectra were obtained with the Southern African Large Telescope (SALT) (Buckley et al. 2006; O′Donoghue D. et al. 2006) on 12 and 20 April 2012. We used the Robert Stobie Spectrograph (Burgh et al. 2003) to make two 600 s. exposures with the grating GR900 and two 900 s. ones with GR2300. The slit width was 1.25″ and the position angle PA=146°. The final reciprocal dispersions are 1.78 and 0.34 Å pixel^{-1} and the corresponding spectral resolution FWHM= 3 and 1 Å for the spectra taken with the two gratings, respectively. The reduction of the SALT long-slit data was done in the way described in Kniazev et al. (2008). Primary reduction of the data was done with the SALT science pipeline (Crawford et al. 2010).

The data reduction and analysis of the OHP observations were performed using MIDAS and IRAF. The dispersion solution provides an accuracy of ∼0.08 Å for the wavelength calibration. Possible systematics in the wavelength calibration due to instrumental flexure were studied using the [OI]λ5577 night sky line in the dispersion-corrected spectra, and by comparison of synthetic and observed spectra using the full spectrum fitting methods and constructing a detailed line-spread function of the spectrograph (LSF) (see e.g. Koleva et al. 2009).

Finally the one-dimensional lower-resolution SALT spectrum was flux calibrated using the corresponding OHP spectrum and summed with it. The S/N in the resulting spectrum reaches ∼15 at 4300 Å, ∼50 at 5000 Å and ∼160 at 6300 Å. The resolution of the spectrum obtained with the grating GR2300 is FWHM= 1Å and the mean S/N at 4740 Å is ∼ 40. The final medium-resolution spectrum of the CS is shown in Fig.1. The high-resolution spectrum was used separately to estimate C^{12}/C^{13}, as explained in Sect. 5.

3 RADIAL VELOCITY

The heliocentric radial velocity of our star was derived by cross-correlation with the spectrum of the star APM 2229+1902 using the IRAF FXCOR package. Before cross-correlation we subtracted the continuum using the IRAF task *continuum* and high-order polynomials. The cross-correlation shift (object-template) is 1.32 pixels. The radial velocity of our star is $V_h = -163 \pm 26$ km/s, taking into account a relative systematic shift (object-template) derived from fitting of the night sky lines (-1.2 - (-0.7)=-0.5 pix), and heliocentric corrections of -26 and -10 km/s, respectively, for our star and the template APM 2229+1902 (which has a radial velocity V_h =-348 km/s). We also used a more robust PPXF method (Cappellari & Emsellem 2004) to measure the radial velocity on the same spectra. The result of the fitting is illustrated in Fig.2. Maximum penalized likelihood suppresses the effect of noise in the solution, so the accuracy is higher. Applying the aforementioned corrections, the resulting heliocentric radial velocity is $V_h = -159 \pm 5$ km/s. Both estimates are close to the radial velocity of NGC 6426 $V_h = -162 \pm 23$ (Harris 1996, 2010 edition). The probability that the CH star belongs to the field is very low, because using the Besançon model (Robin et al. 2003), we find that the distribution of radial velocities of the 428 stars in the V magnitude range 10 to 18 located within 10′ of the centre of the cluster is centered around a mean velocity of +13.22 km/s, with a dispersion of 53.52 km/s.

4 PHOTOMETRIC INFORMATION

The photometric data for our CH star and the ones in NGC 6402 and Ω Cen, and two classical Galactic CH stars from the atlas of CSs by Barnbaum et al. (1996) are listed in Table 1. The successive lines are: (1) apparent visual distance modulus from Harris (1996, 2010 edition) (2) absolute magnitude in the V-band corrected for Galactic extinction, (3) Galactic extinction from Schlegel et al. (1998), (4-9) broadband optical and infrared colors corrected for Galactic extinction, (10) effective temperature.

To estimate the coordinates of the CH star in NGC 6402, we first obtained approximate coordinates on images

Table 1. Optical and 2MASS photometric data for CH stars. See text for details. All the colors were corrected for Galactic extinction.

	N6426	N6402	RGO 55	RGO 70	HD5223	V Ari
$(M-m)_0$	16.58	16.71	13.97	13.97	9.75	9.19
M_V	-2.58	-1.86	-2.39	-2.36	-1.43	-1.14
E(B-V)	0.36	0.60	0.12	0.12	0.04	0.14
B-V	1.69	1.90	1.56	1.68	1.43	2.14
V-I	1.59	-	1.45	1.31	-	-
V-K	3.52	-	-	-	2.82	3.73
J-H	0.69	-	0.67	0.73	0.53	0.48
H-K	0.18	-	0.23	0.20	0.17	0.26
J-K	0.87	-	0.90	0.93	0.70	0.66
T_{eff}, K	4100	-	4468	4287	4360	3600

from the CFHT archive[2], and then identified it more accurately on HST images. These coordinates are: RA(J2000)= $17^h37^m36\overset{s}{.}94$; Dec(J2000)= $-03°14\overset{\prime}{.}5\overset{\prime\prime}{.}31$. The colors and magnitudes for stars in NGC 6426 in the optical bands were published by Hatzidimitriou et al. (1999) and Dotter et al. (2011), using ground-based and HST images, respectively. Unfortunately, our star is saturated on the HST images. In the color-magnitude diagram of Hatzidimitriou et al. (1999) it is the reddest star in the cluster, slightly brighter than the stars at the tip of the red giant branch. Photometric data in the B, V, and I bands for the CH stars in NGC 6402 and Ω Cen were taken from Cannon & Stobie (1973), Côté et al. (1997) and Pancino (2007). Unfortunately, the CH star in NGC 6402 is too close to another star of same magnitude to obtain reliable near-infrared magnitudes from either 2MASS or Denis[3]. The data for HD5223 and V Ari were extracted from the SIMBAD astronomical database.

We calculated the near-infrared colors of the stars in the *SAAO* and *TCS* photometric systems using the 2MASS colors and the transformation equations from Carpenter (2001) and Ramírez & Meléndez (2004). With the colors thus derived, corrected for Galactic extinction, our star definitely falls in the box delimiting CH stars in the two-color diagnostic diagram in the SAAO photometric system by Totten et al. (2000). Its effective temperature calculated using relations from Alonso et al. (1999) and the $(J-K)_o$ color in the TCS photometric system is $T_{eff} = 4100 \pm 125$ K. This corresponds to the class CH4 of Keenan (1993), which is equivalent to spectral type K4 III for oxygen stars. Similarly, the T_{eff} of RGO 55 and RGO 70 are 4468K and 4287K, respectively.

5 SPECTRAL ANALYSIS

5.1 Classification

The spectrum of the CH star was examined visually in terms of different spectral characteristics (Goswami 2005) to avoid possible misclassification with C-N and R type CSs, which have spectra similar to those of CH stars. We compared the spectrum of the CH star with spectra at almost the same resolution for other such objects in the literature (e.g Barnbaum et al. 1996; Goswami 2005) and found an approximate similarity in the shape of the main spectral features

[2] http://www1.cadc-ccda.hia-iha.nrc-cnrc.gc.ca
[3] http://cdsweb.u-strasbg.fr/denis.html

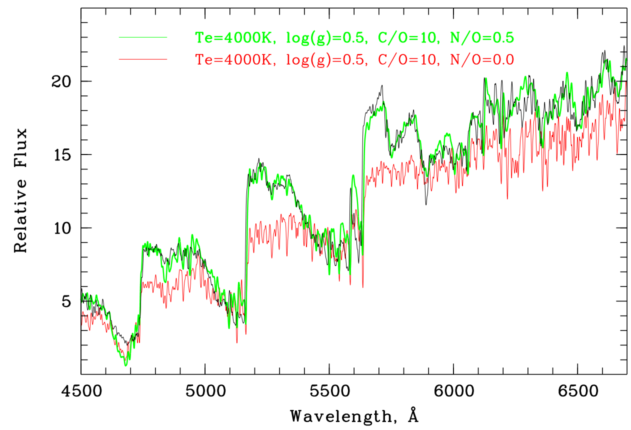

Figure 3. Observed medium-resolution spectrum of the CH star in NGC 6426 (black) fitted with the model one (green): T_{eff} = 4000K, $log(g)$ = 0.5, C/O= 10, N/O= +0.5. A model spectrum with lower N abundance is shown in red.

with the spectra of two classical CH stars: HD5223 (type C-H3, C_2 index 4.5) and HD13826 (V Ari) (type C-H3.5, C_2 index 5.5). HD 5223 is a CH giant (see Fig. 1) with [Fe/H]= −2.0 dex, C/O= 3.0, V Ari is a semi-regular pulsating star with [Fe/H]= −2.4, $log(g) = -0.2$, C/O= 2, and $^{12}C/^{13}C \sim 6-10$ (Aoki & Tsuji 1997; Goswami 2005). The strength of *the G band of CH (∼4300 Å)* in the spectrum of our star, *a main characteristic feature of CH-type CSs*, resembles that in the spectrum of HD 5223, and the same applies to the second branch near 4342 Å. The line at 4226 Å is very weak. It is blended by molecular bands. The lines of atomic hydrogen and BaII are seen distinctly, which is not the case in C-R stars. The intensity of the CN band in our star is larger than in the case of HD 5223 and V Ari. The C_2 molecular bands near 4737, 5165, 5635, 6052 Å are deeper than in HD 5223. This indicates a lower temperature for our star and/or a higher C/O ratio (Barnbaum et al. 1996; Goswami 2005).

CH stars are classified into two types which follow distinct evolutionary paths based on their $^{12}C/^{13}C$ ratios (e.g Goswami 2005). Late-type CH stars with $^{12}C/^{13}C \geqslant 100$ are intrinsic asymptotic branch (AGB) stars that produce the s-process elements internally. Early-type CH stars with low values $^{12}C/^{13}C \leqslant 10$ obtain the s-process elements via binary mass transfer. This is why the $^{12}C/^{13}C$ ratio is an important probe of stellar evolution. The band heads for $^{12}C^{12}C$, $^{12}C^{13}C$ and $^{13}C^{13}C$ (at 4737Å, 4744Å and 4752Å, respectively) are resolved even at medium resolution. In the following we will estimate $^{12}C/^{13}C$ and other parameters as accurately as possible using model atmospheres.

5.2 Hydrostatic dust-free models

To estimate the effective temperature, surface gravity, C/O and $^{12}C/^{13}C$ for the CH star in NGC 6426 we used the hydrostatic dust-free models for carbon-rich giants of Aringer et al. (2009) extended towards higher T_{eff}, $log(g)$, and C/O to fit the observational data. We chose the following model parameters: stellar mass $1M_{\odot}$, metallicity

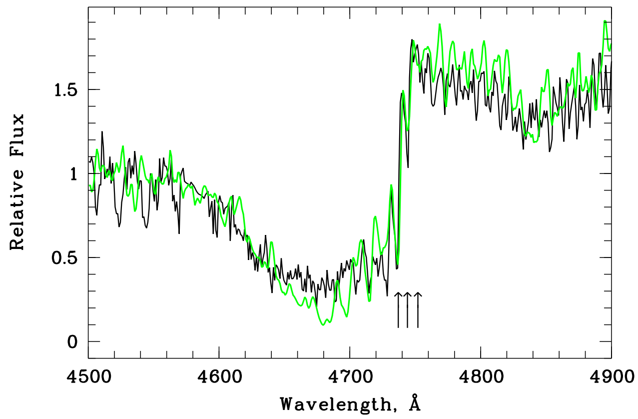

Figure 4. SALT spectrum of the CH star in NGC 6426 taken at the resolution of FWHM∼ 1Å. The model with T_{eff} = 4000K, $log(g)$ = 0.5, C/O= 10, N/O= +0.5 is shown for comparison in grey. The band heads of $^{12}C^{12}C$, $^{12}C^{13}C$ and $^{13}C^{13}C$ are indicated by arrows.

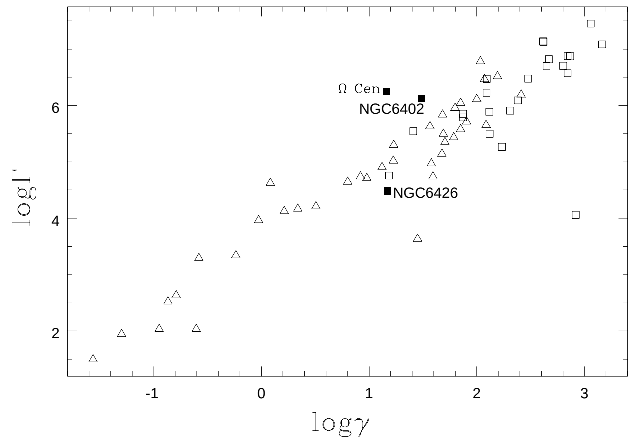

Figure 5. Survival of a binary star. The total encounter rate Γ is plotted vs the encounter rate γ for single binaries. Globular clusters with concentration parameters c < 1.60 are indicated by triangles, the others by squares. The three globular clusters which harbour CH stars are indicated by full symbols. The units are arbitrary on both axes.

[Fe/H]= −2.0 dex, and solar abundance for the other elements including the isotopic ratio $^{12}C/^{13}C$ = 86.8 (Scott et al. 2006). The metallicity was chosen equal to the metallicity of NGC 6426 (given by Harris 1996, 2010 edition). The model stellar mass roughly corresponds to the mass of stars at the Main-Sequence turnover point of NGC 6426 (Hatzidimitriou et al. 1999). Unfortunately, it is not possible to derive more accurate values of the mass and chemical abundance of the star, given the resolution of our spectra.

The synthetic spectra computed with the COMA code based on COMARCS model atmospheres (see Aringer et al. 2009) were degraded by convolution with a Gaussian function to fit the resolution of our data. The resulting synthetic colors were compared with the observed ones, providing additional arguments for a proper evaluation of the stellar parameters.

To obtain a good fit of the observational data with the model (both photometric and spectroscopic) we had to change not only the abundance of Carbon, but also those of N and O, because only increasing C at a given T_{eff}, $log(g)$ did not allow us to fit the CN bands. A moderate increase of O with dredge up or mass transfer is expected for carbon stars (e.g Lugaro et al. 2012, and references therein). Finally, we derived the following model parameters: T_{eff} = 4000K, $log(g)$ = 0.5, C/O= 10, [N/Fe]= +0.5 dex, [O/Fe]= +0.5 dex which corresponds to an absolute magnitude $M_V = -2.57$ and the following synthetic colors: $B-V = 1.71$, $V-K = 3.44$, $V-I = 1.57$, $J-H = 0.67$, $H-K = 0.24$, $J-K = 0.91$. One can see from Table 1 that the agreement between the observed and model spectra and between the spectroscopic and photometric T_{eff} has been reached in a wide spectral range.

Fig. 3 shows how this model fits our medium-resolution spectra. Although our aim was not to estimate the abundances of different chemical elements on these spectra, the depth and shapes of the main molecular bands are fairly well adjusted. We did not vary the isotopic ratio $^{12}C/^{13}C$, since there is no significant difference between the shape and depth of the C_2 bands in the model and those in the spectrum in the range 4737 - 4752 Å. Fig. 4 shows the comparison between the higher resolution spectrum of the CH star and the best fit model. The increased N abundance allows the strong CN features to be better matched. The derived luminosity, T_{eff}, $log(g)$ and the high isotopic ratio $^{12}C/^{13}C$ indicate that this is probably a *genuine* AGB star. The derived T_{eff} is normal for C-rich TP-AGB stars at a very low metallicity (Marigo et al. 2008).

6 SURVIVAL OF BINARIES IN GLOBULAR CLUSTERS

We now examine the alternative possibility that the CH star is a binary star rather than a genuine AGB star.

The dense environment of GCs favors the formation of binary stars, which in turn play an important role in their dynamical evolution, by delaying the onset of core collapse (e.g. Heggie et al. 2006). This dense environment may also lead to the dissolution of the wider binaries, so that the actual number of binaries depends on the central stellar density and core radius (Verbunt 2003), as well as on their separation.

In Fig. 5 we show the total encounter rate $\Gamma \propto \rho_c^{1.5} a r_c^2$ versus the encounter rate $\gamma \propto \rho_c^{0.5} a/r_c$ for single binaries (Verbunt 2003) for globular clusters in the halo (defined as having $[Fe/H] < -0.80$ dex). The parameters were calculated using the core radii r_c and central luminosity densities ρ_c from Harris (1996, 2010 edition) and the mass-to-light ratios from McLaughlin & van der Marel (2005). We assumed that the M/L of NGC 6426, not available in the catalogs, is ∼1.9, which is the most probable value for Galactic GCs at low metallicities. The uncertainty on this M/L is small (of the order of 10%). We also assumed that all binaries have the same semi-major axis a, which is a more drastic simplification.

The clusters are aligned along a relation of almost unit slope between the two encounter rates. The three GCs with known CH stars fall roughly in the middle of the relation. If all four CH stars are binaries, this suggests that no binaries can form when the total encounter rate is low, and that they are more rapidly disrupted than replenished if the encounter rate for single binaries is high. The number of known CH stars in clusters is admittedly too small to allow for any statistical inference on the probability of our CH star to be a binary. The three GCs have similar γ, but the parameter Γ is lower in NGC 6426 than in the two other clusters, thus making our star perhaps less likely to be a binary star. But, as pointed out by Verbunt (2003), Γ depends on the mass segregation, on the fraction of binaries and on their period distribution. Furthermore, both Γ and γ depend linearly on the semi-major axis, for which we assumed a universal value, but which can vary between a few and at least 200 $R_{\odot}$, so that presently a better way to determine the binary status of our star would be to monitor its radial velocity.

7 CONCLUSION

We have discovered a Carbon star of CH type in NGC 6426 and derived its main physical and chemical parameters: $M_V = -2.58$ mag, $T_{eff} = 4000-4100$ K, $log(g) \sim 0.5$, [Fe/H]~ -2 dex, C/O$\sim$ 10, N/O$\sim$ +0.5 dex, $^{12}C/^{13}C \sim 87$. The data and the estimated encounter rates in the parent GC indicate that the object is likely an *intrinsic* low-metallicity carbon-rich AGB star, but additional extensive high-resolution observational and theoretical studies are needed to reveal the role of a possible presently invisible companion on its evolution.

ACKNOWLEDGMENTS

We thank Dr. Goswami for providing spectra of CH stars and Prof. Sarajedini for sending us a table with the photometry of NGC 6426, and J.-P. Troncin, who helped in the OHP observations. M. S. acknowledges partial support of grants GK. 14.740.11.0901, and RFBG 11-02-00639-a. BA acknowledges support from Austrian Science Fund (FWF) Projects AP2300621 & AP23586. This research is based on observations obtained with the South African Large Telescope, program 2011-3-RSA-003, and it made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Note : After this paper was accepted for publication and posted on arXiv we were informed that three more carbon star are known in the globular cluster Ω Cen (Jacco van Loon et al., MNRAS 382, 1353, 2007).

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