АСТРОФИЗИКА

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EXTENSION OF THE C STAR ROTATION CURVE OF THE MILKY WAY TO 24 kpc

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Demers and Battinelli published, in 2007 the rotation curve of the Milky Way based on the radial velocity of carbon (C) stars outside the Solar circle. Since then we have established a new list of candidates for spectroscopy. The goal of this paper is to determine the rotation curve of the Galaxy, as far as possible from the Galactic center, using N-type C stars. The stars were selected from their dereddened 2MASS colours, then the spectra were obtained with the Dominion Astrophysical Observatory and Asiago 1.8 m telescopes. This publication adds radial velocities and Galactrocentric distances of 36 C stars, from which 20 are new confirmed. The new results for stars up to 25 kpc from the Galactic center, suggest that the rotation curve shows a slight decline beyond the Solar circle.

Key worsds: *Stars:carbon stars:kinematics Galaxy:kinematics and dynamics*

1. *Introduction.* The surface mass distribution of the Milky Way is still poorly constrained, even while our knowledge of Galactic stellar abundance distribution grows ever more detailed. One reason for this shortcoming is the difficulty to determine the Galactic rotation curve in the outer disk. Battinelli and Demers [1] discovered numerous carbon (C) stars in the outer disk of M31 reaching 40 kpc. Such C stars are certainly also present in the Milky Way. Indeed, N-type C stars can be used as kinematical probes. They are intrinsically bright, $\langle M(I) \rangle = -4.6$ [2]. Moreover, these intermediate-age stars are old enough to have lost memories of their initial kinematic conditions with which they might have been (i.e. motion within parent cluster/association). At the same time, these stars are still relatively young, with smaller random velocities than older tracers (e.g. planetary nebulae). They are believed to be members of the thin disk population [3].

An important characteristics of the N-type C stars is their small dispersion in the absolute magnitude, which allows to use as reliable candles when some color criteria are adopted (see papers [4,5] for more details).

Demers and Battinelli [6] established the Galactic rotation velocity up to distance of 15 kpc using genuine N-type C stars. In that paper they adopted the following common criteria for the intrinsic colors to select disc candidates, $(J-K)_0 > 1.4$ and $(H-K)_0 > 0.45$, plus additional restrictions on photometric limits to avoid high reddening regions and dust-enshrouded C stars which would lead to unreliable results.

The present paper is a follow-up of the publication [6]. We refer to paper [6] for a detailed description of the methods for candidate selection, data reduction, radial velocity determination, distance estimates. Radial velocity targets are selected from the 2MASS (Two Micron All - Sky Survey Catalogue) [7] with colors corresponding to N-type C stars. Stars are dereddened using Schlegel et al. [8] reddening software. We exclude stars within 3° from the Galactic plane to avoid high uncertain reddening. The new data set includes targets that are calculated to be as far as 24 kpc from the Galactic center. To reach that far we had to relax our selection criteria to include candidates with Galactic latitiudes $3° < |b| < 9°$. We then become limited by faintness of the candidates which cannot be properly acquired by the guiding system of the telescope.

2. *New Observations.* The new spectra, discussed in this paper, were obtained between July 2007 and January 2010. We used the spectrograph attached to the Cassegrain focus of the Dominion Astrophysical Observatory (DAO, Canada) 1.8 m Plaskett Telescope. The same spectroscopic setup for the observations in October 2006 was selected. The spectral region covered ranges from 6100 Å to 6800 Å. Because our previous experience showed that 24% of the selected targets on the basis of $(J-K)_0$, are not carbon stars but mostly emission-line objects. In 2009 we initiated a low-dispersion spectroscopic survey, with the 1.8 m telescope at Asiago (Italy), equipped with the Asiago Faint Object Spectrometer and Camera (AFOSC), to confirm the nature of the stars to be observed at the DAO. We obtained spectra in the range 3700-8000 Å (grism №4, dispersion 4.2 Å /pixel).

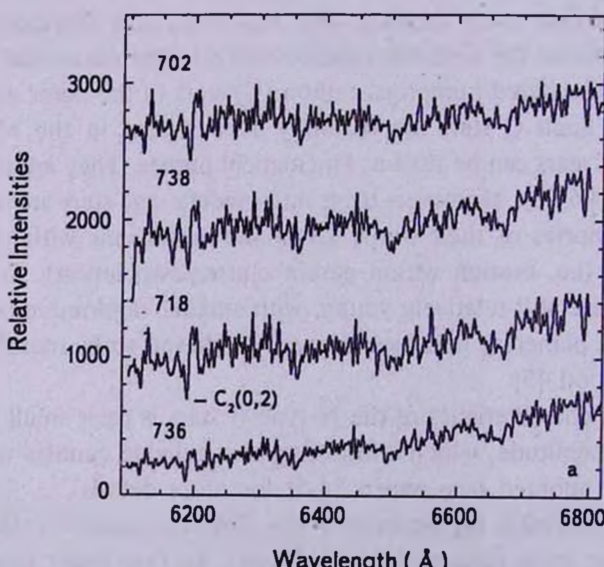

Fig.1a, b. Examples of higher-resolution DAO spectrum (Fig.1a) of the new C stars in the range 6100-6800 Å. Spectra are smoothed by 5 pixel box car. Absorption band of the C_2 (0, 2) Swan system at bandhead 6192 Å is indicated. Fig.1b presents low-resolution spectrum obtained at Asiago, on January 4, 2009. Swan bands of the C_2 molecule is noted.

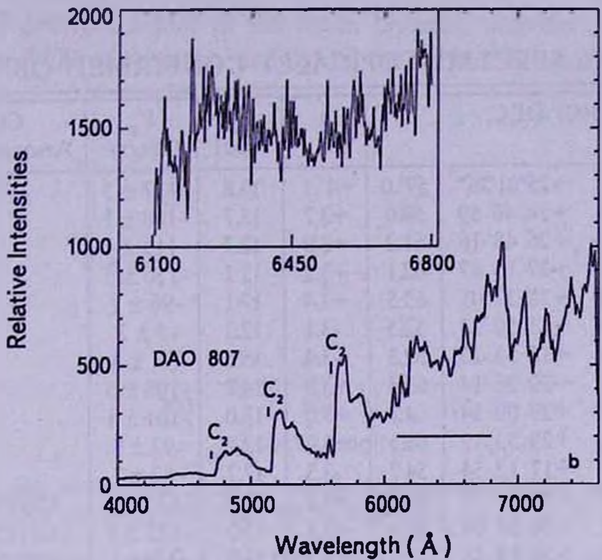

Fig.1a, b. The end

Further more, in addition to those used during the previous runs, we selected in 2007 and 2010 three other carbon stars for radial velocity standards. They are CGCS 4285 (CGCS - Cool Galactic Carbon Stars, Alksnis et al.) [9] (V_h = +50 km/s) and CGCS 10 (V_h = -70.2 km/s). Their radial velocities are published by Aaronson et al. [10]) and Metzger and Schechter [11]. To avoid large uncertainties in the rotation velocity, no C stars closer than 45° from the anticenter were observed. This survey is still active and being out in collaboration with Byurakan Astrophysical Observatory (BAO, Armenia).

In Fig.1a, b we present a few examples of spectra of new confirmed C stars.

3. *Data Analysis.* This publication adds 36 new radial velocities and Galactocentric distances of spectroscopically confirmed C stars. The stars are listed in order of their J2000.0 right ascension in Table 1. We give our own running numbers because many of them are not in the CGCS Catalogue [9], l and b are Galactic coordinates, d_G is the distance to the Galactic center in kpc and the Heliocentric velocities with errors are in km/s., when available, the association with the CGCS [9], is also reported in the Table 1.

We discovered, after the spectra were taken, that star №718 is among the stars observed by Aaronson et al. [10]. They quote V_h = -72 km/s while we have V_h = - 69 ± 2 km/s. The Heliocentric distance of each star is estimated using its apparent K magnitude, reddening and absolute K magnitude based on its $(J-K)_0$ and following the relation between M_K and the intrinsic $(J-K)_0$ color, used in Demers and Battinelli [6].

$$M_K = -6.31 - 0.99(J-K)_0 \quad (1)$$

Table 1

DATA FOR 36 SPECTROSCOPICALLY CONFIRMED OBJECTS

Star №	RA. (J2000)	DEC.	l	b	d_G (kpc)	V_H (km/s)	CGCS Association [8]
701	$19^h25^m57^s.7$	+25°01'36"	59°.0	+4°.1	13.8	-127 ± 3	
702	19 27 41.6	+24 46 59	50.0	+3.7	15.7	-108 ± 1	
703	19 31 18.9	+26 48 16	61.2	+3.9	12.7	-113 ± 4	
704	19 36 11.3	+27 15 47	62.1	+3.2	12.1	-115 ± 5	
705	19 38 39.4	+28 37 01	63.5	+3.4	17.1	-96 ± 2	
706	19 39 33.9	+15 50 23	52.5	-3.1	12.2	-5 ± 3	
707	19 40 07.8	+15 33 23	52.3	-3.4	15.5	-91 ± 4	
708	19 41 14.1	+30 26 14	65.4	+3.8	14.2	-108 ± 5	
709	19 41 45.8	+29 09 54	64.3	+3.0	13.0	-101 ± 1	
710	19 42 35.3	+29 53 19	65.1	+3.2	12.7	-92 ± 8	
712	19 44 45.5	+17 12 54	54.7	-3.3	17.7	-52 ± 7	
714	19 49 40.5	+34 21 57	69.7	+4.2	13.2	-125 ± 6	CGCS 4510
715	19 52 53.2	+20 51 09	58.4	-3.3	15.2	-113 ± 1	CGCS 4539
717	19 58 58.2	+36 13 38	72.3	+3.5	12.3	-100±4	CGCS 4592
718	20 02 14.0	+36 42 02	73.0	+3.2	13.4	-69±2	CGCS 4625
719	20 02 56.7	+37 00 56	73.4	+3.2	14.8	-135±4	
721	20 08 55.9	+39 28 35	76.1	+3.6	14.9	-144±2	
722	20 14 48.9	+40 12 17	77.3	+3.0	15.2	-130±1	CGCS 4773
725	20 19 53.7	+41 47 29	79.2	+3.1	13.7	-48±11	
726	20 27 39.8	+31 12 20	71.4	-4.2	15.2	-137±3	
845	21 30 38.5	+45 06 55	90.0	-4.5	18.1	-120±2	CGCS 5330
1007	20 52 32.1	+30 34 01	74.1	-8.9	16.9	-117±4	
728	20 54 31.5	+39 42 11	81.5	-3.4	13.8	-126±3	CGCS 5030
1008	21 09 28.0	+34 51 07	79.8	-8.8	24.0	-173±5	
1010	21 59 06.0	+45 39 01	94.2	-7.4	17.6	-165±6	
732	22 06 19.1	+61 00 53	104.2	+4.3	13.4	-71±2	CGCS 5580
1011	22 20 57.5	+47 23 23	98.3	-8.1	21.3	-120±5	CGCS 5633
733	22 51 10.4	+64 14 57	110.3	+4.4	14.1	-128±3	
734	23 08 01.3	+55 49 24	108.7	-4.2	16.8	-154±4	CGCS 5811
735	23 38 44.3	+58 16 43	113.5	-3.3	15.8	-119±2	CGCS 5904
736	23 46 48.8	+58 08 41	114.5	-3.7	13.5	-70±1	CGCS 5932
737	00 51 04.9	+59 30 15	122.9	-3.4	12.0	-107±4	CGCS 123
738	01 12 42.0	+59 44 50	125.6	-3.0	13.4	-80±1	CGCS 186
805	01 20 00.5	+54 02 26	127.2	-8.6	21.4	-117±3	CGCS 210
807	02 03 31.6	+55 52 15	133.0	-5.6	24.5	-86±4	CGCS 6023
809	02 09 23.2	+54 27 51	134.2	-6.7	20.1	-107±4	

The Galactocentric distances for our stars were computed assuming a distance between the Sun and Galactic center $D_{Sun} = 7.62 \pm 0.32$ kpc (Eisenhauer et al.) [12]. The velocities relative to the LSR were computed adopting the Solar motion from the Dahnen and Binney [13]. Finally, the rotation velocities were computed as described in section 5 of the paper [6].

4. *Results and discussion.* Intermediate-age C stars belong to the thin

disk. Fig.2 presents a plot of the mean Galactic latitude of what we call C stars, some 4400 of them (as defined by their 2MASS colors). The means are

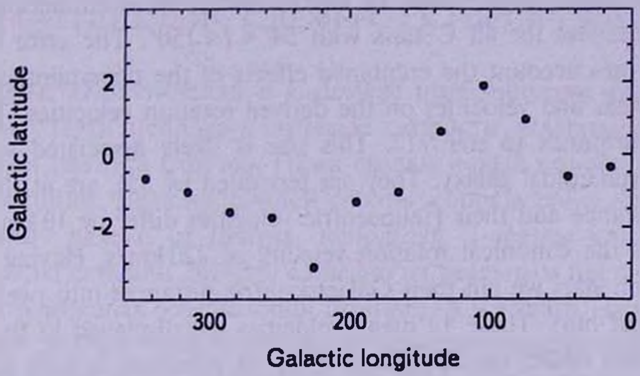

Fig.2. A plot of the mean Galactic latitude (in degrees) of the C stars outside the Solar circle. The means are taken over a 30° bin in longitude.

taken over 30° bin in longitude. We select only stars outside the Solar circle and with Galactocentric distances less than 30 kpc, to exclude extragalactic objects of similar NIR colors. We see a well defined warp, confirming the results by Momany et al. [14] for the thin disk. In that paper authors, using the RGB stars, detected an extended stellar population out to a distance of

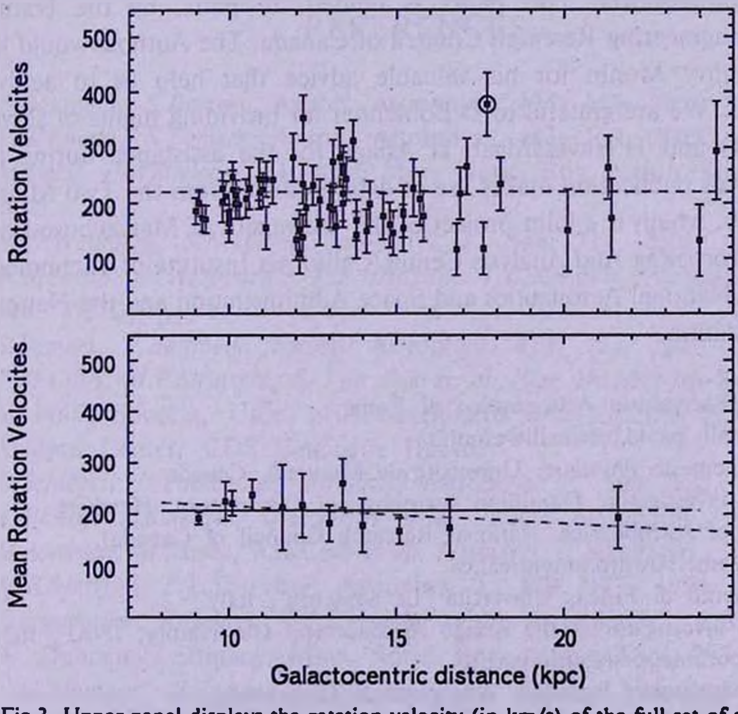

Fig.3. Upper panel displays the rotation velocity (in km/s) of the full set of stars. The lower panel shows the rotation curve when the stars are binned by group of six. Error bars are explained in the text.

24 kpc from the Galactic center and a stellar warp similar to that of Fig.2.

Our results are summarized in Fig.3 where the stars from the paper [6] are also included. The upper panel shows the circular velocities as a function of the Galactocentric distances for all C stars with $54° < l < 150°$. The error bar are computed taking into account the combined effects of the uncertainties in the heliocentric distances and velocities on the derived rotation velocities. The dot with a circle corresponds to star 712. This star is likely associated with the Sagittarius dwarf spheroidal galaxy. They are separated by 35°, are at the same Galactocentric distance and their Heliocentric velocities differ by 10 km/s. The dashed line traces the canonical rotation velocity of 220 km/s. Having now a total 71 disk carbon stars we bin their Galactocentric distances into twelve bins of six (5 in the first bin). These 12 mean velocities are displayed in the lower panel. The error bars reflect the dispersion of the six velocities in each bin. The solid line marks the mean velocity of $\langle V \rangle = 205$ km/s. In this panel the dashed line is a least square solution indicating a slight decline.

The new data presented here, allow us to trace the roration curve to 24 kpc, an extension of some 9 kpc to the 2007 results. The results presented in Fig.3 show that most stars farther than 12 kpc have rotation velocities less than 200 km/s and the trend confirms that the rotation curve of the Galaxy is declined beyond the Solar circle, as suggested in paper [6].

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РАСШИРЕНИЕ КРИВОГО ВРАЩЕНИЯ УГЛЕРОДНЫХ ЗВЕЗД МЛЕЧНОГО ПУТИ ДО 24 кпк

П.БАТТИНЕЛЛИ[1], С.ДЕМЕРС[2], К.РОССИ[3], К.С.ГИГОЯН[4]

В 2007г. П.Баттинелли и С.Демерс опубликовали кривую вращения Млечного Пути используя лучевые скорости углеродных (С) звезд за пределами радиуса Солнца. Нами создан новый список кандидатов для спектроскопии. Цель настоящей работы - определение кривой вращения Галактики далеко от центра, используя С-звезды классов N. Звезды отобраны из каталога 2MASS, согласно их реальным цветам, и наблюдены на 1.8-м телескопах обсерватории Доминиона и Азиаго. Данная публикация добавляет лучевые скорости и галактоцентрические расстояния для 36 С-звезд, из которых 20 установлены впервые. Новые результаты, для звезд до 25 кпк расстояния от центра Галактики, показывают тонкий уклон кривого вращения за пределами солнечного расстояния.

Ключевые слова: *Звезды:углеродные-звезды:кинематика Галактики:динамика*

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