Cume 338: Galaxies

Passing grade for the cume is 33 points. This article provides numerous details regarding a dwarf irregular galaxy Cam B. The galaxy is normal in many respects. It has rotation (see fig 7). Distribution of light has normal exponential profile. There is neutral hydrogen (see fig 4 and eq.1). The paper gives parameters for all these components.

1. **5pt** The abstract states that, when corrected for asymmetric drift, the galaxy is on the Tully-Fisher relation. What is the Tully-Fisher relation?

2. **5pt** Estimate the absolute magnitude of our Galaxy assuming that both galaxies are on the TF relation with the slope 8.5.

3. **5pt** The authors find that "corrected rotation curve cannot be fitted with an NFW halo regardless of the assumed mass to light ratio". What is an NFW halo? Mass to light ratio of what component is discussed here?

4. **5pt** What is the circular velocity $v_c(r)$ and how is it related to the mass $M(r)$?

5. **5pt** In equation 2 the quantities on the right hand side are measured quantities of neutral hydrogen. Their combination gives the circular velocity. Is the circular velocity also for gas only? What do we do with stars and with dark matter? Do we correct the equation for He? Are they missed in the equation?

6. **10pt** Using the corrected rotation curve given in fig 7 estimate the mass of the dark matter inside the radius of 1.2 kpc. Please, do not forget that there is gas and stars in the galaxy. When making estimates, assume that the distribution of mass is spherically symmetric and assume that M/L for stars is about unity in solar units.

7. **10pt** Using the equation of hydrostatic equilibrium (aka the Jeans equation) derive equation 2. Assume that the rms velocity of gas clumps σ does not change much with distance ($d\ln\sigma^2/d\ln r \approx 0$) and assume that the surface density is proportional to the gas density in the plane of the disk: $\Sigma(r) = C\rho(r, z = 0)$, where C is a constant. The pressure due to random motions with velocity dispersion σ^2 is equal to $P = \rho\sigma^2$, where ρ is the gas density.

8. **10pt** Measured profile of circular velocity $v_c(r)$ sometimes is used to estimate the density profile of dark matter $\rho_{dm}(r)$. Write an equation, which relates $v_c(r)$ and $\rho_{dm}(r)$.

Relations and constants

- Gravitational constant $G \approx 1/(15 \cdot 10^6)$ $cm^3/s/gram$
- $1pc = 3.08 \cdot 10^{18}$ cm
- 1 radian = 206265 arc sec
- $M_\odot = 2 \cdot 10^{33}$ gram

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The little galaxy that could: kinematics of Camelopardalis B

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Abstract

We present deep, high velocity resolution (~ 1.6 km s^{-1}) Giant Meterwave Radio Telescope HI 21 cm synthesis images, as well as optical broad band images, for the faint ($M_B \sim -10.9$) dwarf irregular galaxy Camelopardalis B. We find that the HI in the galaxy has a regular velocity field, consistent with rotational motion. Further, the implied kinematical major axis is well aligned with the major axis of both the HI flux distribution as well as that of the optical emission. Camelopardalis B is the faintest known galaxy with such relatively well behaved kinematics. From the HI velocity field we derive a rotation curve for the galaxy. The rotation curve can be measured out to galacto-centric distances >4 times the optical scale length. The peak (inclination corrected) rotation velocity v_o is only ~ 7 km s^{-1}—the high velocity resolution of our observations was hence critical to measuring the rotation curve. Further, the peak rotational velocity is comparable to the random velocity σ of the gas, i.e. $v_o/\sigma \sim 1$. This makes it crucial to correct the observed rotation velocities for random motions before trying to use the kinematics to construct mass models for the galaxy. After applying this correction we find a corrected peak rotation velocity of ~ 20 km s^{-1}. On fitting mass models to the corrected rotation curve we find a good fit for a constant density halo with a density of $\rho_0 \sim 12\ M_\odot\ pc^{-3}$. This density is well determined, i.e. it has a very weak dependence on the assumed mass to light ratio of the stellar disk. We also find that the corrected rotation curve cannot be fit with an NFW halo regardless of the assumed mass to light ratio. Finally we compile from the literature a sample of galaxies (ranging from normal spirals to faint dwarfs) with rotation curves obtained from HI synthesis observations. The complete sample covers a luminosity range of ~ 12 magnitudes. From this sample we find: (i) that Camelopardalis B lies on the Tully–Fisher relation defined by these galaxies, provided we use the corrected rotation velocity, and (ii) a weak trend for increasing halo central density with decreasing galaxy size. Such a trend is expected in hierarchical models of halo formation.

PACS: 95.75.Kk; 95.35.+d; 98.62.Dm; 98.56.Wm

Keywords: Dark matter; Galaxy: kinematics and dynamics; Galaxies: individual: Camelopardalis B; Galaxies: dwarf; Line: profiles

1. Introduction

There are a number of reasons why kinematical studies of faint dwarf galaxies are particularly interesting. The first is related to the structure of the dark matter halos of galaxies. Traditionally, dark matter

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individual frames were added after shifting them to a common coordinate system.

Cam B has a relatively irregular optical morphology (see Fig. 3). Because of the bad seeing, it was not possible to determine whether the knotty structures seen in the B band image were barely resolved stars or HII regions, consequently the distance to Cam B could not be estimated from this data set. The irregular morphology however means that the images needed to be smoothed before attempting surface photometry; a gaussian 10 arc sec (FWHM) filter was used for this purpose. Surface photometry was done using the ellipse fitting algorithm of Bender and Möllenhoff (1987). The average ellipticity of Cam B was found to be 0.53±0.16 (corresponding to an inclination of ~65° for an intrinsic thickness ratio $q_0 = 0.25$, see Section 5). The overall orientation of the optical major axis in the B (V) band data is 210° (199°) degrees, in good agreement with the orientation of the HI data (see below). At the northern rim, a very faint, fuzzy extension is visible in the V-band (and to a much smaller extend in the B-band) which changes the PA of the outermost isophotes toward a slightly lower value of 189°, but still in good agreement with the overall distribution of the radio data. This extension is related to the color gradient seen in Fig. 1, which shows the surface brightness profiles in the B and V bands. Exponential fits to the surface brightness profiles are shown superposed. The exponential scale lengths are 26.2″ for the V band and 22.6″ for the B band. The corresponding linear quantities (at an adopted distance of 2.2 Mpc) are 0.28 kpc and 0.24 kpc respectively. From the figure it can also be seen that $B-V$ is approximately constant in the inner regions of the galaxy (up to ~35″), while a color gradient is seen in the outer regions of the galaxy. Finally a mask at the 26.5 mag per square arc second level was constructed in order to determine the flux in both filters within the Holmberg isophote. The total B and V magnitudes within the 26.5 mag per square arc sec are found to be 16.71 and 15.91 respectively. The absolute Holmberg magnitude obtained (after correcting for Galactic extinction using A_B=0.93 mag and A_V=0.72 mag, Schlegel et al., 1998), are $M_B = -10.94$ and $M_V = -11.52$. Note that no correction for internal extinction has been applied. The corresponding B and V luminosities are $L_B = 3.7\times10^6\ L_\odot$ and $L_V = 3.5\times10^6\ L_\odot$. We also note that the low value of the central surface brightness (Fig. 1) makes Cam B an LSB galaxy.

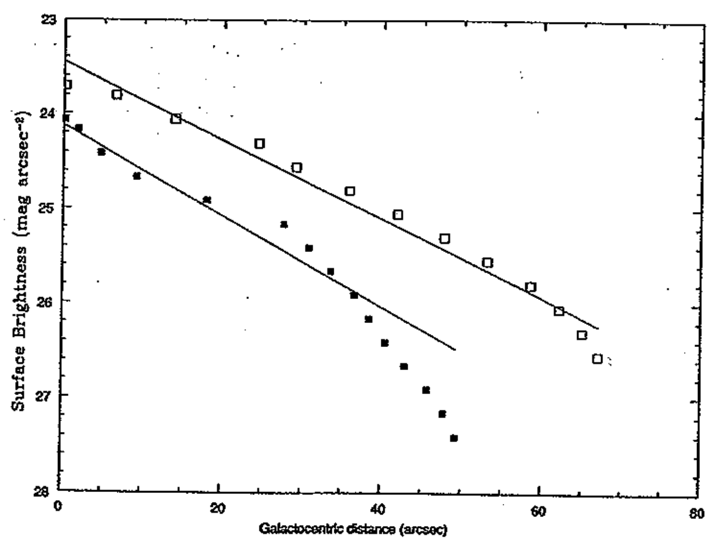

Fig. 1. Surface brightness profile of Cam B in the B (filled squares) and V (empty squares) bands. The best fit exponential profiles are shown superimposed.

The global HI emission profile of Cam B is given in Fig. 2. A Gaussian fit to the profile gives a central velocity (heliocentric) of 77.5±1.0 km s^{-1}. The integrated flux is 4.6±0.4 Jy km s^{-1}. These are in excellent agreement with the values of 77.0±1.0 km s^{-1} and 4.47 Jy km s^{-1} obtained from single dish observations (Huchtmeier et al., 2000). The excellent agreement between the GMRT flux and the single dish flux shows that the no flux was missed because of the missing short spacings in the interferometric observation. The velocity width at 50% level of peak emission (ΔV_{50}) is found to be 21.4±1.0 km s^{-1}, which again is in reasonable agreement with the ΔV_{50} value of 18 km s^{-1} determined from the single dish observations. The HI mass obtained from integrated profile (taking the distance to the galaxy to be 2.2 Mpc) is $5.3\pm0.5\times10^{6}$ $M_{\odot}$, and the M_{HI}/L_B ratio is found to be 1.4 in solar units.

We examined the line profiles at various locations in the galaxy and found that they were (within the noise) symmetric and single peaked. Moment maps i.e. maps of the total integrated flux (moment 0), the flux weighted velocity (moment 1) and the flux weighted velocity dispersion (moment 2) were then made from the data cubes using the AIPS task MOMNT. To obtain the moment maps, lines of sight with a low signal to noise ratio were excluded by applying a mask at 3σ level, σ being the rms noise

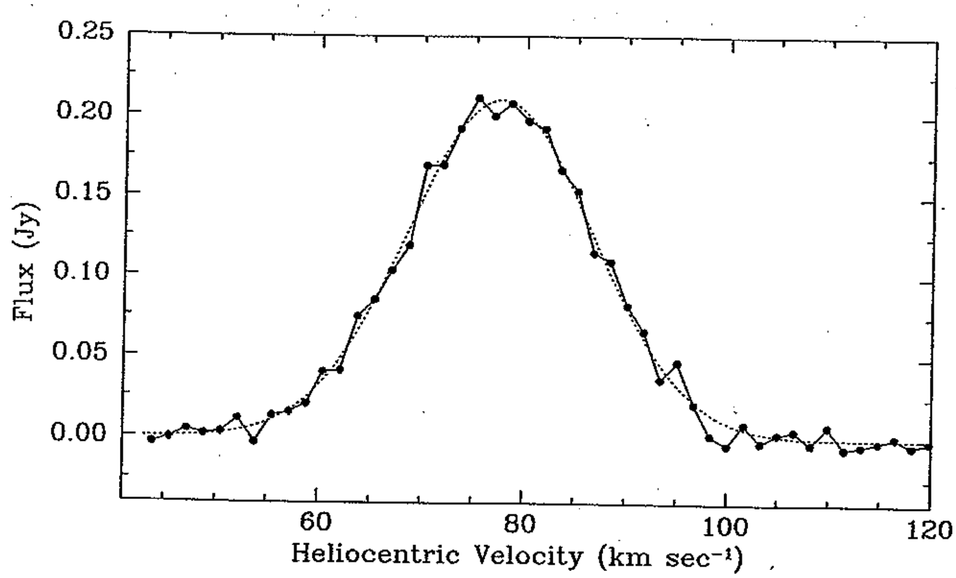

Fig. 2. The global HI profiles of Cam B as derived from the GMRT data. The channel separation is 1.65 km s^{-1}. The dotted line shows a Gaussian fit to the line profile.

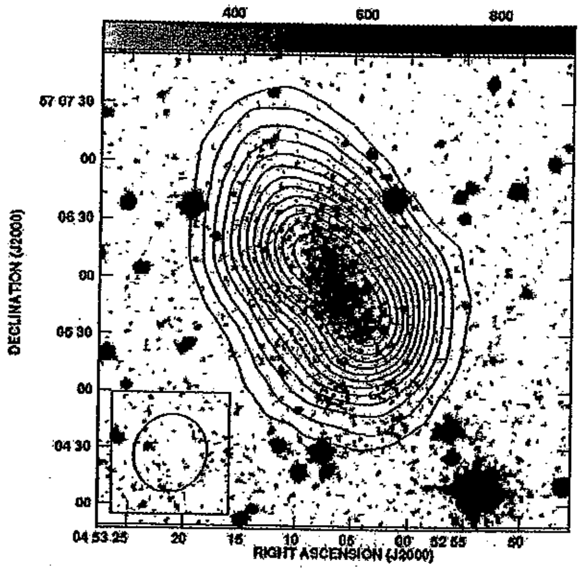

Fig. 3. The digitized Palomar Sky Survey image of Cam B with the GMRT 40″×38″ resolution integrated HI emission (moment 0) map overlayed. The contour levels are 3.7, 8.8, 19.1, 24.3, 29.4, 34.6, 39.8, 44.9, 50.1, 55.2, 60.4, 65.5 and 70.7×10^{19} atoms cm^{-2}.

Fig. 3 shows the integrated HI emission at 40″× 38″ arcsec resolution overlayed on the digitized sky survey image of Cam B. Consistent with the optical image the HI isophotes suggest that galaxy is seen at a fairly high inclination. Fig. 4 shows the deprojected radial surface density profile of the HI obtained from fitting elliptical annuli to the HI moment 0 image. A gaussian fit is shown superimposed; as can be seen the surface density $\Sigma_{\rm HI}(r)$ is well represented by a Gaussian:

$$\Sigma_{\rm HI}(r) = \Sigma_0 \times e^{-r^2/2r_0^2} . \tag{1}$$

with $r_0 = 40.7'' \pm 1.6''$ (corresponding to a linear scale of 0.43 kpc) and $\Sigma_0 = 5.9 \pm 0.2\ M_\odot\ pc^{-2}$.

The inclination of the HI disk was determined

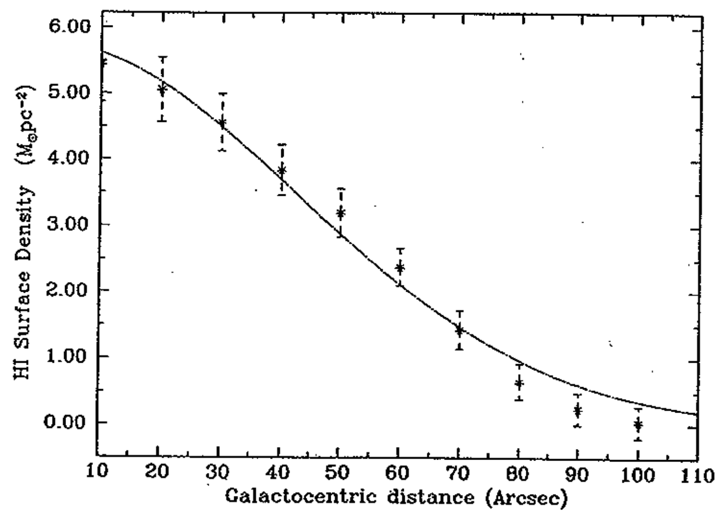

Fig. 4. The HI surface density profile derived from the HI surface density shown in Fig. 3. A gaussian fit is shown superimposed.

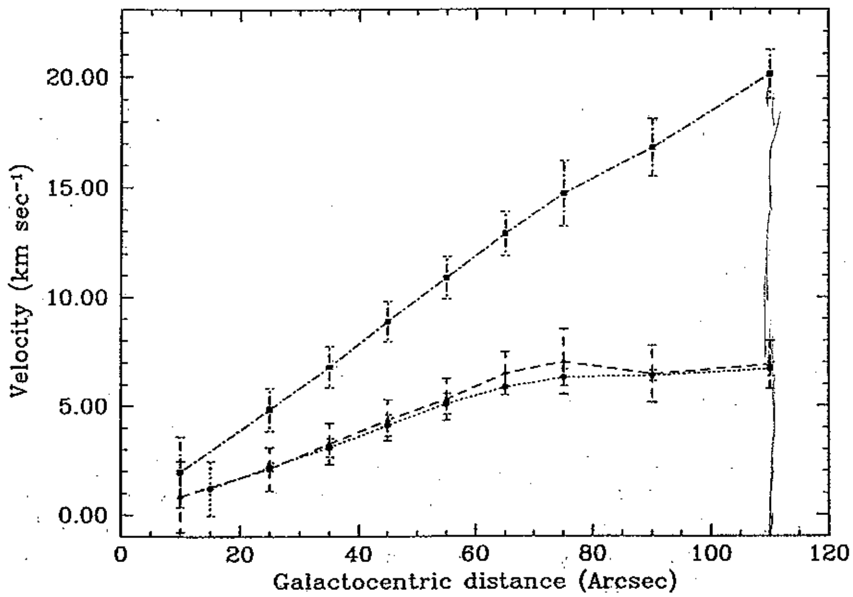

Fig. 7. The final adopted rotation curve (dashes), the rotation curve after beam smearing (dots) and the rotation curve after applying the asymmetric drift correction (dash dots).

random motions provide significant dynamical support to the disk. Equivalently, the observed circular velocity significantly underestimates the centripetal force and hence the implied dynamical mass. The observed rotation velocities hence need to be corrected before trying to estimate the dynamical mass. This correction, generally termed an 'asymmetric drift' correction is given by (e.g. Meurer et al., 1996; note that the formula below is slightly different from the one in Meurer et al., 1996 since we have used a sech^2 profile in the vertical direction instead of an exponential one)

$$v_c^2 = v_o^2 - r \times \sigma^2 \left[\frac{\mathrm{d}}{\mathrm{d}r} (\ln \Sigma_{\mathrm{HI}}) + \frac{\mathrm{d}}{\mathrm{d}r} (\ln \sigma^2) - \frac{\mathrm{d}}{\mathrm{d}r} (\ln 2h_z) \right],$$

where v_c is the true circular velocity, v_o is the observed rotation velocity, σ is the velocity dispersion, and h_z is the scale height of the disk. Strictly speaking, asymmetric drift corrections are applicable to collisionless stellar systems for which the magnitude of the random motions is much smaller than that of the rotation velocity. However, it is often used even for gaseous disks, where the assumption being made is that the pressure support can be approximated as the gas density times the square of the random velocity. For the case of Cam B, in the absence of any direct measurement of h_z we assume $\mathrm{d}(\ln(h_z))/\mathrm{d}r = 0$, (i.e. that the scale height does not change with radius) and also use the fact that σ^2 is constant across the galaxy, to get:

$$v_c^2 = v_o^2 - r \times \sigma^2 \left[\frac{\mathrm{d}}{\mathrm{d}r} (\ln \Sigma_{\mathrm{HI}}) \right]. \quad (2)$$

Using the fitted Gaussian profile to the radial surface density distribution, (see Eq. (1)) we obtain

$$v_c^2 = v_o^2 + r^2 \sigma^2 / r_0^2. \quad (3)$$