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DARK MATTER IN THE MILKY WAY GALAXY

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Abstract. We probe the gravitational mass of our Galaxy using 21-cm spectral line. The observations were performed on the Small Radio Telescope (SRT) of the Astronomical observatory of Sofia University. We have estimated that the content of the dark matter is approximately 56% of the total Milky Way mass interior to 8.5 kpc, assuming a solar Galactocentric distance of 8.5 kpc.

1. INTRODUCTION

In astrophysics and cosmology, dark matter is a matter which does not emit and does not reflect any electromagnetic waves (see e.g. Einasto 2009). Dark matter has unknown nature, but its presence can be only inferred from gravitational effects on visible matter. Astronomers frequently determine the mass of the objects by studying their emissions.

2. KINEMATICS OF GALACTIC ROTATION

Since the frequency of the 21-cm hydrogen line is known (see e.g. MIT Department of Physics 2004), measurements of the redshift at various galactic longitudes allow for calculating the velocity of the source using the equation describing the Doppler shift:

$$\mp V = \frac{\pm \Delta\nu}{\nu} c, \tag{1}$$

where V is the velocity of approach $(-)$ or recession $(+)$, c is the speed of light, $\Delta\nu$ is the frequency shift, and ν is the rest frequency (for HI, $\nu = 1420.4$ MHz).

For observations with galactic longitudes $0^\circ \leqslant l \leqslant 90^\circ$, the hydrogen is receding from the observer. Thus, the frequency of hydrogen is expected to be "redshifted", that is, lower than the rest frequency. The point of interest (where measurements are performed) is the point P (Fig. 1). The line of sight is labeled by "Direction of antenna beam"; naturally, the antenna beam intersects the point P. The antenna beam makes an angle γ with the Galactic center; this angle is also the Galactic longitude l. The velocity $V_{\rm SRT}$ of the neutral hydrogen (HI) at the point P on the SP-axis (Fig. 1) detected by the Small Radio Telescope (SRT) is given by the relation (see e.g. Clemens 1985, Binney and Merrifield 1998, Varghese 2008):

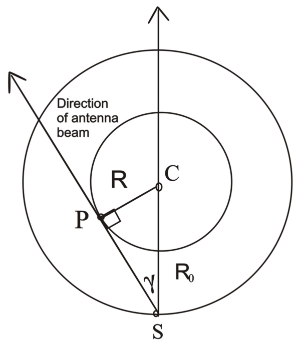

Figure 1: Simplified geometry of Galactic motion.

$$V_{\mathrm{SRT}} = V - V_{\odot} \sin\gamma, \tag{2}$$

where V is the real orbital velocity of the neutral hydrogen at the distance R and $V_{\odot}$ is the Sun's orbital velocity. Bearing in mind that the Sun's orbital velocity is

$$V_{\odot} = \omega_0 R_0, \tag{3}$$

where ω_0 is the angular velocity and R_0 is the radius of the point S measured from the Galactic center. We get that

$$V = V_{\mathrm{SRT}} + \omega_0 R_0 \sin\gamma. \tag{4}$$

Let us note that above formula is applicable when observations are performed in quadrants $0^\circ \leqslant l \leqslant 90^\circ$ and $270^\circ \leqslant l \leqslant 360^\circ$ (see e.g. Clemens 1985).

This geometry is based on a simplified model referencing motion relative to the Sun. Since both the motion of the Sun and the motion of the observer on Earth need to be considered, it is best to describe motion relative to the local standard of rest (LSR). The LSR is defined as "the centroid of motion of the stars near the Sun or local region of our home area of the Galaxy" (see e.g. Varghese 2008). These considerations are implemented in the Doppler shift calculation (1). The full expression for the source velocity V is

$$V = \frac{\Delta\nu}{\nu} c - V_{\mathrm{LSR}}. \tag{5}$$

Then, for the maximum redshifted frequency $\nu_{\mathrm{max\ shift}}$, the maximum velocity of emission of the neutral hydrogen is that velocity, which is detected by the Small Radio Telescope:

$$V_{\mathrm{SRT}} = \frac{\nu - \nu_{\mathrm{max\ shift}}}{\nu} c - V_{\mathrm{LSR}}, \tag{6}$$

where ν is the rest frequency (for HI, $\nu = 1420.4$ MHz) and V_{LSR} is the velocity along the line of sight relative to the LSR.

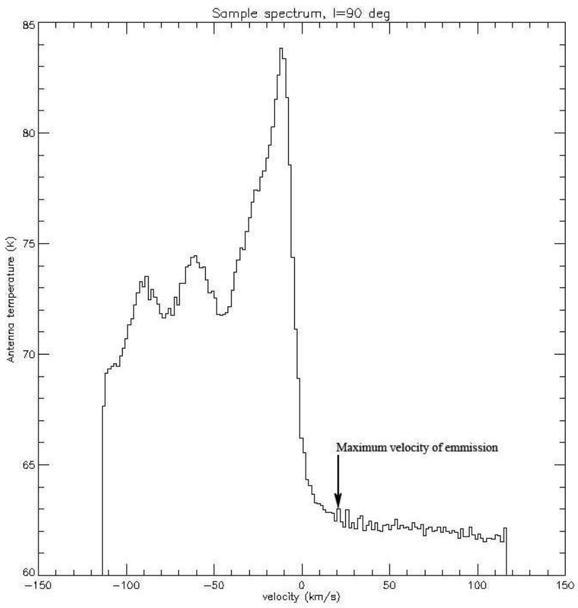

Figure 2: The spectrum of the neutral hydrogen emission at Galactic longitude $l = 90°$ and Galactic width $b = 0$, registered over 120 seconds. The "Maximum velocity of emission" ($V_{\rm SRT} = 20{\pm}5$ km/s) is determined by the first pick with maximum intensity of the antenna temperature possessing positive velocity. That pick corresponds to the Doppler shift.

3. RESULTS

From the hydrogen spectrum, shown in Fig. 2, we determined the value of the maximum velocity of emission, notably $V_{\rm SRT} = 20 \pm 5$ km/s. We have adopted the radial velocity of the Sun and its distance to the Galactic center recommended by International Astronomical Union (IAU) in 1985 (see e.g. Reid 1993) to be

$$V_\odot = \omega_0 R_0 = 220 \pm 15 \text{ km/s} \quad \text{and} \quad R_0 = 8.5 \pm 0.5 \text{ kpc}, \tag{7}$$

respectively. Consequently, we substitute these values in formula (4) and obtain the magnitude of the radial velocity V of the neutral hydrogen at Galactic longitude $\gamma = 90°$:

$$V = 240 \pm 20 \text{ km/s}. \tag{8}$$

In the point-mass gravity approximation the orbital velocity V at the distance R_0 is

$$V = \sqrt{\frac{GM}{R_0}}. \tag{9}$$

Then the total gravitational mass $M_{\rm grav}^{\rm SRT}$ of the Milky Way at the distance $R_0 = 8.5$ kpc is:

$$M_{\rm grav}^{\rm SRT} = \frac{V^2 R_0}{G} = (1.14 \pm 0.01) \times 10^{11} M_\odot. \tag{10}$$

According to Wentzel (see e.g. Wentzel 1998) $M_{\rm grav} = 1.0 \times 10^{11} M_{\odot}$ at the same distance, which means that our result is fully acceptable. But the gravitational mass $M^{\rm SRT}_{\rm grav}$ is the sum of the dark and visible matter of the Galaxy:

$$M^{\rm SRT}_{\rm grav} = M_{\rm DM} + M_{\rm vis}. \tag{11}$$

We take the orbital velocity of the Sun to be equal to 160 ± 15 km/s (see e.g. Nicolson 1999). Hence, the visible mass of Milky Way at distance 8.5 kpc from the center of the Galaxy is:

$$M_{\rm vis} = (5.06 \pm 0.05) \times 10^{10} M_{\odot}.$$

This value is comparable to the estimation of the visible mass in our Galaxy $\approx 5 \times 10^{10} M_{\odot}$) at distances between 3 and 5 kpc (see e.g. Sommer-Larsen and Dolgov 2001). Then we can calculate the content of the dark matter in the Galaxy:

$$M_{\rm DM} = M^{\rm SRT}_{\rm grav} - M_{\rm vis} = (6.34 \pm 0.12) \times 10^{10} M_{\odot} = (1.25 \pm 0.04) M_{\rm vis}.$$

Thus the contribution of the dark matter interior to 8.5 kpc in our Galaxy is $(56.0 \pm 1.2)\%$ and that of the visible matter is $(44.0 \pm 0.5)\%$.

4. CONCLUSION

We have estimated the gravitational mass of our Galaxy interior to 8.5 kpc using the 21-cm spectral line. Since the hydrogen radiation is not impeded by interstellar dust this kind of measurements is accurate. We observed deviation from the Keplerian prediction for the velocity of the hydrogen in a circular orbit. We have found that the dark matter in Milky Way contributes to approximately 56% the total mass of the Milky Way at the distance of 8.5 kpc and the contribution of the visible matter is only 44%. The problem of dark matter in galaxies and clusters is still unresolved.

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