Hydrostatics of the Galactic halo

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Abstract.
We investigated a hydrostatic equilibrium model of the Milky Way following Parker (1966), to constrain the large scale properties of the interstellar medium. In our approach we found an excellent agreement between our simple hydrostatic equilibrium model of the Milky Way and the recent all-sky survey data ranging from the $\gamma$-ray to the radio regime.

On large scales the galactic disk-halo system is found to be stable against Parker-instabilities. Pressure support from the Galactic disk is essential to stabilise the halo. In particular the diffuse ionised gas layer acts as a disk-halo interface.

Assuming that the distribution of the soft X-ray emitting plasma traces the gravitational potential, we derived the dark matter content of the Milky Way to be about $M \approx 2.8 \times 10^{11} \, M_{\odot}$. Our findings are consistent with the rotation curve of the Galaxy.

1. Introduction

Since the early fifties it is known from optical polarisation studies, that magnetic fields are constituents of the Galactic interstellar medium. The magnetic field strength is about a few $\mu$G. Radio continuum observations clearly indicate synchrotron radiation originating high above the Galactic plane. Thus, magnetic fields and cosmic rays are obviously constituents of the Galactic halo. But what is about the gas within the Galactic halo? Already Parker (1966) showed, that magnetic fields are always associated with the gaseous phase. Investigations in the UV-range show that highly ionised gas is common within the halo, but it is a long way from a pencil beam to the whole volume of the Galactic halo.

Recent investigations of the ROSAT soft X-ray background data indicated the existence of a pervasive X-ray emitting plasma ($T \approx 1.5 \times 10^6$ K) with a vertical scale height of about 4.4 kpc (Pietz et al. 1998) within the halo. Moreover, a sensitive analysis of the Leiden/Dwingeloo H I survey gave evidence for a H I emission component with a high velocity dispersion of 60 km s$^{-1}$ (Kalberla et al. 1998) also detectable across the entire sky. The discovery of both gas components within the Galactic halo encouraged us to study the hydrostatic equilibrium model of the Milky Way once again. For this approach we studied recent all-sky surveys of H I gas, soft X-ray radiation, high energy $\gamma$-ray emission, and radio-continuum emission.
2. A gaseous halo

To describe the large-scale properties of the Milky Way we used the approach of a hydrostatic halo model, as proposed by Parker (1966). To describe the gaseous disk-halo system, we identified 3 main constituents of the Galactic interstellar medium, namely: the neutral interstellar gas with $h_z = 400$ pc (Dickey & Lockman, 1990), the diffuse ionised gas (DIG) with $h_z = 950$ pc (Reynolds, 1997), and halo gas with $h_z = 4.4$ kpc (Kalberla et al. 1998, and Pietz et al. 1998). The major difference to the previous studies of the hydrostatic equilibrium of the Milky Way (e.g. Bloemen 1987, Boulare & Cox 1990) is the detailed knowledge about the gas phase in the Galactic halo. In particular, the X-ray plasma in combination with the H\textsc{i} high-velocity dispersion component adds major physical parameters to our model.

Fig. 1 displays the vertical density distributions of the gas phases (diffuse neutral and ionised gas as well as the X-ray plasma) in the solar vicinity. Fig. 2 gives an impression on the radial density distribution represented by the parameter $g_1$ according to Taylor & Cordes (1993) with $A_1 = 15$ kpc.
3. Gas, magnetic field and cosmic rays in equilibrium

Following Parker’s (1966) suggestion, we studied whether gas, magnetic fields and cosmic rays in the Galactic halo may be in pressure equilibrium. Indeed, hydrostatic equilibrium models fit the all-sky-averaged observations best. In detail we tested the hydrostatic equilibrium model by modelling the Galactic synchrotron emission at 408 MHz as observed by Haslam et al. (1982), the γ-ray emission as observed with EGRET at energies > 100 MeV (Fichtel et al. 1994) as well as by modelling the Galactic X-ray plasma distribution deduced from the ROSAT all-sky survey data (Pietz et al. 1998). A detailed discussion of the model calculations and a quantitative comparison with the observations are beyond the scope of this contribution; for details we refer to Kalberla & Kerp (1998). Here we summarise the main features of the model. We found a pressure equilibrium between gas, magnetic fields and cosmic rays within the Galactic halo. The magnetic field of the Galactic halo is globally regularly ordered and orientated parallel to the Galactic plane. In contrast to the halo the magnetic field within the disk is highly irregular and has only 1/3 of the gas pressure.

4. Mass distribution and gravitational forces

For a galaxy in hydrostatic equilibrium the 3-D distributions of gas pressure, density and gravitational potential are identical in size and shape. Accordingly, we can utilise our parameterisation of the Milky Way to deduce the gravitational potential and the dark matter content.

In a simple view, the Galaxy consists of 3 main parts: the Galactic bulge, the stellar disk with a radial scale length of 4.5 kpc and the gaseous halo as described above. Assuming that the gaseous halo traces the dark matter distribution we
Figure 4. The gravitational acceleration $K_z$ in the solar neighbourhood (solid line) deduced from the presented hydrostatic equilibrium model including the derived dark matter content. For comparison $K_z$ derived by Kuijken & Gilmore (1989) (dotted line) and Bienamé et al. (1987) (dashed line) is given for $|z| < 5$ kpc. The differences between the individual $K_z$ curves for $z > 1.5$ kpc are due to different model assumptions concerning the Galactic halo.

optimised the density of the gaseous halo component until the rotation velocity of the modelled distribution was in quantitative agreement with the observed rotation velocities (i.e. Fich et al., 1990) within galactocentric radii $3 < R < 25$ kpc. Fig. 3 shows the corresponding rotation curve. The total mass of the Galaxy within $R = 50$ kpc derived from our model is $M = 2.8 \cdot 10^{11} M_\odot$, consistent with $M = 2.4 \cdot 10^{11} M_\odot$ (Little & Tremaine, 1987) and also within the uncertainties with the results of Kochanek (1996) of $M = 4.9 \cdot 10^{11} M_\odot$.

In Fig. 4 we show the gravitational acceleration $K_z$ in the solar neighbourhood as a function of $z$ deduced from our model in comparison to that of Kuijken & Gilmore (1989) and Bienamé et al. (1987). Within vertical distances of $z < 1$ kpc our model (solid line) is in excellent agreement with $K_z$ derived by Kuijken & Gilmore (1989) (dotted line) and Bienamé et al. (1987) (dashed line). The differences at larger $k_z$ distance is because of different model assumptions on the dark matter distribution. The turn-over of our model about 5 kpc above the disk is because of the radial dependence of $K_z$, as shown in Fig. 5 (the solar radius is marked by the dotted line).

5. Summary and conclusion

The large scale properties of the Galactic halo are very well modelled assuming that the main constituents of the interstellar matter, the gas, the magnetic fields, and the cosmic rays are in hydrostatic equilibrium. We analysed recent all-sky surveys of H1 gas, soft X-ray radiation, high energy $\gamma$-rays and synchrotron radiation to test the model assumptions. In general we find good quantitative agreement between model and data. The assumption that the gaseous halo
traces the dark matter in the Galaxy leads to a total mass which is consistent with the observed rotation curve.

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Leo Blitz: I’m concerned about the reality of the 60 km/s component. First, I don’t see how it’s possible to have a static ISM with such highly supersonic velocities. Second, the component is not seen in the Bell Labs survey which has very good instrumental sidelobe response. I can understand how baselines can introduce features in a spectrum, but I don’t see how a bad baseline can coincidentally remove a feature from all over the sky.

Peter Kalberla: The reality of the 60 km/s component was discussed in detail by Kalberla et al. (1998, A&A 332, L61). For a comparison between the Bell Labs and Leiden/Dwingeloo surveys concerning broad emission lines see Kalberla et al. (1997, in Proceedings of the IAU Colloquium No. 166 “The Local Bubble and Beyond”, eds. D. Breitschwerdt, M.J. Freyberg, J. Trümper, Lecture Notes in Physics 506, 475). The fact that the observed line width of 60 km/s exceeds the thermal H$^\text{i}$ line width significantly does not imply that the H$^\text{i}$ gas is in supersonic motion. The H$^\text{i}$ gas in the halo has a volume filling factor of 0.12 only. One has to consider the motion of individual H$^\text{i}$ eddies with respect to the surrounding plasma. Since the sound velocity of this plasma is more than twice as high as the typical H$^\text{i}$ eddy velocity of 60 km/s, the motions of the H$^\text{i}$ clumps are clearly subsonic. Dissipative cloud-cloud collisions are of little relevance in a multiphase halo.