A possibility of Magnus effect on disk galaxies

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The Magnus effect introduced near the turbulent boundary layer in the flow of rotating disk galaxies in the intergalactic medium (IGM) is discussed. The Magnus effect is expected to develop an extra pressure on the outer edges of the gas disk in galaxies. It is found that for the Milky Way, the pressure due to Magnus effect is significant compared to the thermal pressure and the gravitational restoring pressure in the gas disk. It is speculated that the Magnus effect is playing some role in maintaining various morphological asymmetries in disk galaxies. Due to higher IGM densities at high redshifts, the role of the Magnus effect on galaxies is expected to be crucial at earlier epochs.

Keywords: Galaxy evolution, hydrodynamics, intergalactic medium, Magnus effect.

THE lateral force experienced by rotating bodies in a fluid is called the Magnus effect[1]. The Magnus effect plays an important role in describing motion and lift of aerofoils and rotating bodies in aerodynamics[2]. The mathematical formulism of the Magnus effect can be provided by the Kutta–Joukowski theorem, which is described in the textbooks of fluid dynamics[2,3]. This theorem states that the pressure difference produced on the sides of a moving aerofoil or a rotating body in a fluid is proportional to the product of circulation near the boundary layer, velocity of the flow and density of the fluid medium. The circulation can be produced by the characteristic shape of the aerofoil or by providing a rotation in case of a cylindrical or spherical body. The circulation is given by $2\pi R^2\omega$ for a circular body of radius R rotating with angular velocity ω.

The intergalactic medium (IGM) can be considered to be a fluid interacting with the interstellar matter (ISM) in the galaxies, as the mean free path of gas particles in the IGM is much less compared to size of the galaxy. The flow of IGM past the galaxy has been modelled using hydrodynamic relations and is believed to be having subtle effects on the gas disks, particularly in removing gas from the disks[4–7]. Kahn and Woltjer[4] proposed that moving gas disks can be bent due to the IGM pressure. Subsequently, Gunn and Gott[5] predicted that the ram pressure can remove gas from galaxies in a viscous medium. Later, Livio *et al.*[6] and Nulsen[7] described the role of turbulence and viscosity in gas-removal processes. The effect of rotation of disk galaxies on the IGM flow has not been considered explicitly in any of these descriptions of ISM–IGM interaction.

It can be expected that galaxy rotation in IGM will give rise to the Magnus effect. The Magnus effect will introduce a pressure difference across the outer edges of the galaxy. Consequently, the Magnus effect will be realized as the outward pressure acting on the edges of the gas disk. The Magnus effect is operative when the flow is turbulent, as it requires the boundary layer to be much thinner than the size of the obstacle[2,3]. In the viscous medium, it has been shown that the rotation of the galaxy does not affect the gas in the disk[8]. However, the effect of rotation in turbulent flows has not been described earlier, although the flow of IGM can be highly turbulent in some galaxy environments. We describe here the astrophysical conditions where the Magnus effect can be significant. The estimates of the Magnus effect on galaxies are carried out in the following paragraphs. Some consequences of the Magnus effect on galaxy disks are also speculated here.

The ISM to IGM density ratio is typically $>10^3$, indicating that the gas disk in a galaxy can be considered as a rigid body in the IGM fluid. This condition allows us to use conventional fluid dynamics equations for describing the IGM–ISM interactions. The theory of astronomical flows has been described in Dyson *et al.*[9]. As for any fluid dynamical interactions, the Reynolds number will be the deciding parameter for the nature of the IGM–ISM interaction.

The motion of a galaxy creates disturbances in the flow of the IGM around the galaxy. This disturbance will be limited within a mixing boundary layer of finite thickness of the order of $L/\sqrt{R_e}$, where L is the size of the galaxy and R_e the Reynolds number of the flow. The momentum transfer between ISM and IGM will be confined within the boundary layer. The boundary layer separates from the disk behind the flow and turbulence in the form of wakes and vortices can be generated provided the Reynolds number of the flow is sufficiently high. The rotation of the disk will produce asymmetry in the flow along the sides of the galaxy. The IGM flow on the side rotating in the direction opposite to that of the galaxy motion will speed up. It will delay the boundary layer separation on this side compared to that in a non-rotating case. On the opposite side where the direction of rotation and that of the motion of the galaxy are the same, the flow of IGM will be retarded. It will cause a premature separation of the boundary layer. This asymmetric boundary layer separation and difference in the flow speed of IGM will create a difference in the pressure on the two sides, lower pressure being on the side rotating in the direction of motion of the galaxy. The direction of this pressure is outward in the plane of the disk perpendicular to the direction of the angular momentum of the disk and the direction of the galaxy motion. This outward pressure difference on the two sides results in the Magnus effect.

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The pressure difference due to rotation of galaxy is estimated here considering IGM as a completely ionized fluid. Turbulence appears to be pervasive in IGM[10]. It has also been shown that galaxy motions in the clusters can drive the turbulence[11]. Perez-De-Tezada[12] has estimated Magnus force relation for planetary bodies. At high Reynolds numbers, the outward pressure arising out of Magnus effect due to rotation velocity (V_r) of the disk moving with a velocity V in the IGM density (n) can be written as:

$$P \sim \Delta P \sim 1.7 \times 10^{-18}\, n_{-4} V V_r \sim 5.3 \times 10^{-16}\, V_r T_6^{0.5}\, n_{-4} \text{ dyn cm}^{-2}. \quad (1)$$

In the final expression given above, V has been taken as the dispersion velocity (σ) of galaxies in the group and subsequently been converted to IGM temperature (T) following the $\sigma - T$ relation known in groups and clusters[13]. The temperature is written as T_6 in units of 10^6 K and density in units of 10^{-4} cm^{-3} in eq. (1). It has also been assumed that the resulting outward pressure (P) on the sides of the disk is of the order of the pressure difference (ΔP) due to the Magnus effect.

The pressure given by eq. (1) is plotted in Figure 1 for a range of IGM densities and galaxy velocities for a rotation velocity V_r as 200 km s^{-1}. It is worthwhile to mention that the pressure due to the Magnus effect will depend on the direction of the IGM flow with respect to the galactic disk. Galaxies moving face-on in IGM will not experience the Magnus effect, whereas those moving edge-on will have the maximum Magnus effect. This dependence on the orientation is opposite to that due to the ram pressure. In the following paragraph, possible outcomes of the Magnus effect on disk galaxies are speculated.

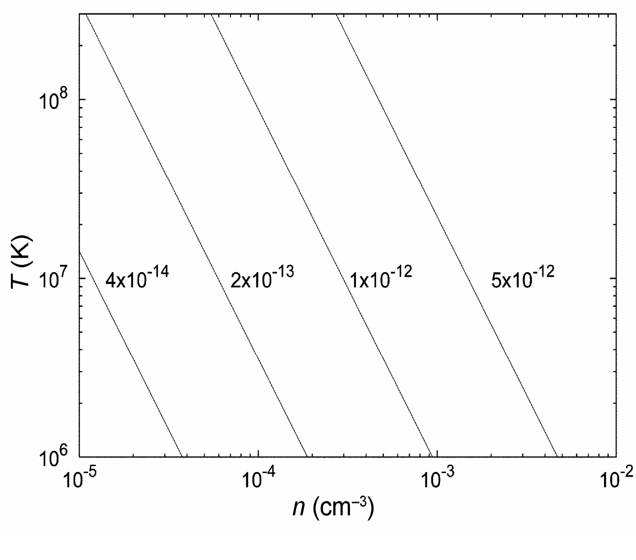

Figure 1. Pressure (dyn cm^{-2}) due to the Magnus effect plotted for a range of IGM temperatures and densities for a galaxy rotating at 200 km s^{-1}.

It will be interesting to estimate the pressure due to the Magnus effect for the Milky Way. Considering the rotation velocity $V_r \sim 300$ km s^{-1} (ref. 14), the radial motion within the local group $V \sim 100$ km s^{-1} (ref. 15) in the IGM density $n \sim 10^{-4}$ cm^{-3} (ref. 16), the maximum pressure due to the Magnus effect is nearly 6×10^{-14} dyn cm^{-2}. The thermal and turbulent pressure in the ISM is $\sim 3 \times 10^{-13}$ dyn cm^{-2} and $\sim 2 \times 10^{-12}$ dyn cm^{-2} respectively[17]. The Reynolds number of the IGM flow will be nearly 30,000, assuming the IGM temperature as $\sim 10^6$ K. The gravitational pressure in the galaxy disk can be given by $m_H \Sigma_g V_r^2 R^{-1}$, where m_H is the mass of the hydrogen atom and Σ_g the column density of gas at radius R. In the case of the Milky Way, assuming $\Sigma_g \sim 10^{19}$ cm^{-2}, the gravitational pressure will be nearly 4×10^{-13} dyn cm^{-2} in the outermost regions. It is evident that the pressure due to the Magnus effect in the Milky Way is significant within 10–20% of the thermal and gravitational restoring pressure in the gas disk.

The stellar disk will remain unaffected due to the Magnus effect. The external pressure in general results into a compression or expansion of the gas. The magnitude of the pressure due to the Magnus effect in group environment can be assumed to be nearly equal to the numerical value of the ram pressure (ρV^2) as $V \sim V_r$ in groups of galaxies. It is evident from Figure 1 that at IGM densities $> 10^{-5}$ cm^{-3} and temperatures $\sim 10^6$–10^7 K, the Magnus effect can produce a significant pressure difference across the gas disk. The Magnus effect produces a pressure gradient along the plane of the disk in a direction perpendicular to both the angular momentum vector and the direction of motion of the galaxy. It is worthwhile to mention here that the effects of the Magnus effect will be limited to the outer edges of the disk and will not propagate into the inner disk of the galaxy. This is due to high Mach number at the edges of the disk than inside it. At high Mach numbers, the effects will always be confined to the edges and at best some asymmetry between the edges of the disk can be expected.

Interestingly, a simulation of ram pressure in the presence of galactic rotation clearly showed interaction of rotation with the galaxy motion[18]. It was found that the gas tail was stretched out to longer distance in IGM on the side rotating in the direction of the IGM flow (i.e. opposite to the direction of galaxy motion) compared to the other side. This behaviour can easily be understood due to the asymmetric boundary layer separation, where the side rotating in the direction opposite to the IGM flow is prematurely separated from the disk and the flow of IGM is retarded. Therefore, this side cannot sweep out enough gas at high velocity from the disk compared to the other side. This particular result from the simulation strengthens the argument that the Magnus effect should be operating on galaxies. Recently, it has been shown that low ram pressure of the order of 10^{-14} dyn cm^{-2} can affect star formation rate and gas morphologies in the outer regions of galaxies[19]. At this moment, it is not obvious how the gas disks will respond to pressure due to the Magnus effect. The hydrodynamical simulations become essential to understand the effect on star formation and galaxy morphology.

A possible instance of the Magnus effect can be attributed to widespread observation of gas lopsidedness in galaxies. It has been known that gaseous and stellar mass distribution in disk galaxies may not be strictly axisymmetric[20]. It now appears that non-axisymmetry or lopsidedness in disk galaxies is a general phenomenon[21]. The strength of lopsidedness is generally higher at larger radii in disks. The origin of lopsidedness is not yet well-understood. A recent review on this subject can be found in the literature[21]. The main problem in various theories proposed to explain lopsidedness lies in sustaining any non-axisymmetry over a few Galactic rotations, which will tend to dilute any kind of non-axisymmetry. Since a large fraction of galaxies show lopsidedness, the mechanism must be acting globally and all the time. The Magnus effect is such a mechanism which can act everywhere and all times in typical galactic environments.

We speculate that the Magnus effect is playing some role in maintaining various gaseous morphological asymmetries in galaxies. It may also be playing a role in modifying star formation rate in the outer regions of the disk, thereby introducing stellar lopsidedness as well. It is to be noted that at high redshifts, the IGM density scales up by $(1 + z)^3$ and therefore outcomes due to the Magnus effect may be crucial at the epochs of formation of galaxies in the past. The hydrodynamical simulations are currently planned to examine the Magnus effect in disk galaxies in different environments.

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Development of cesium fountain frequency standard at the National Physical Laboratory, India

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We discuss the design and development of the cesium fountain frequency standard at the National Physical Laboratory, India. The optical set-up of the fountain needed to capture, cool, launch and detect the cesium atoms is discussed in detail. The concept and design of physical structure of the fountain is also described. In addition, some of our recent results on cooling and trapping of cesium atoms are reported.

Keywords: Atomic clocks, frequency control, laser cooling and trapping, magnetic shielding.

CESIUM (Cs) fountain frequency standards provide precise and accurate measurements of time and frequency.

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