Gas accretion onto galaxies and Kelvin-Helmholtz turbulence

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Abstract

Continued star formation over the lifetime of a galaxy suggests that low metalicity gas is steadily flowing in from the circumgalactic medium. Also, cosmological simulations of large-scale structure formation imply that gas is accreted onto galaxies from the halo inside which they formed. Direct observations are difficult, but in recent years observational indications of gas inflows from a circumgalactic medium were obtained. Here we suggest an indirect observational probe: looking for large-scale (exceeding few kpc) turbulence caused by the accretion. As a specific example we consider an accretion flow coplanar with the galaxy disk, and argue that Kelvin-Helmholtz turbulence will be generated. We employ a semi-analytic model of turbulence and derive the expected turbulence power spectrum. The latter turns out to be of a distinctive shape that can be compared with observational power spectra. As an illustrative example we use parameters of the Milky Way galaxy.

Key words: galaxies-star formation-turbulence-ism

1 Introduction

The observational evidence that star formation goes on continuously in galaxies suggests that there is fresh gas supply from the circumgalactic medium (CGM); (see e.g. Elmegreen (2016); Bland-Hawthorn et al. (2017). Simulations of cosmological large-scale structure formation support this picture; e.g. (Kereš et al. 2005). For a recent review on the physics, astrophysical and observational status of the CGM see Tumlinson, Peeples, & Werk (2017).

Direct observations are difficult; nevertheless, in recent years observation were made suggesting the existence of such an accretion (Elmegreen, Struck, & Hunter 2014; Elmegreen et al. 2016; Kacprzak 2017; Vulcani et al. 2018; Martin et al. 2019; Zabl et al. 2019; Das et al. 2020; Luo et al. 2021; Ianjamasimanana et al. 2022).

Recently, observations carried out for disk galaxies at a redshift \( z \approx 0.2 \) (Ho et al. 2017; Ho, Martin, & Turner 2019; Martin et al. 2019; Ho & Martin 2020) and at redshift \( z \approx 1 \) (Zabl et al. 2019) indicate the existence of cold gas inflowing coplanar with the disk in the near CGM (30–80 kpc) corotating with the disk. The estimated inflow radial velocities are in the range of (20–60) km/s. A very recent simulation by Trapp et al. (2022) conducted for a Milky Way (MW)-type galaxy obtained results consistent with these observations, finding that the deviation of accreting gas from the circular velocity of the galaxy disk gas is quite small and that there is a radial inflow velocity \( \sim 40 \) km/s.

In the present paper we examine a possible observational signature of disk-plane accretion of CGM gas. We find that such an accretion could generate Kelvin-Helmholtz (KH) turbulence at the disk outskirts. Specifically, we address the case in which the inflowing gas is cool and rotates in the same direction as that of the galactic disk, as supported by the observations and simulations; the parameters of the MW galaxy are used as an illustrative example.

The resulting turbulence is large scale (\( \sim 10 \) kpc) with a distinctive velocity power spectrum. There is a range of wavenumbers in which the power spectrum has a logarithmic slope of \( \sim -1 \) which is quiet distinct from the Kolmogorov slope of \( -5/3 \) or \( -2 \) corresponding to compressible turbulence. In order to test the sensitivity of the results to values of the adopted parameters, we repeat the computation with others that are consistent with the observations. While the largest scale of the turbulence and the turbulent velocity do depend on the adopted values of the parameters used, the power spectrum retains its particular shape.

2 Kelvin-Helmholtz Instability

The KH instability (KHI) arises when two fluids with different velocities and (usually) densities form an interface perpendicular to a gravitational field (Chandrasekhar 1961). It is manifested in the case of wind flowing over a body of water, and also in various astrophysical settings (Fleck 1983, 1984, 1989; Gómez & Ostriker 2005; Mandelker et al. 2016; Fleck 2020). In this paper we apply the linear growth rate of the instability in a semi-analytic model of turbulence (Canuto,
Goldman, & Mazzitelli 1996). The latter re-normalizes the growth rate self-consistently taking into account non-linear turbulence. The turbulence model provides the spatial power spectrum of the turbulent velocity field.

The linear growth rate of the KHI is given by Chandrasekhar (1961)

\[ n_s = \sqrt{\alpha_1 \alpha_2 k^2_{\text{rel}} V_{\text{rel}}^2 - \frac{B(k)^2}{2\pi(\rho_1 + \rho_2) k^2} - gk(\alpha_1 - \alpha_2)}, \]

where \( \alpha_1 = \frac{\rho_1}{\rho_1 + \rho_2} \) and \( \alpha_2 = \frac{\rho_2}{\rho_1 + \rho_2} \) with \( \rho_1 \) and \( \rho_2 \) the mass density of the disk and the accreted gas, \( g \) the vertical gravitational acceleration, \( V_{\text{rel}} \) is the relative velocity between the accreted gas and the galactic disk gas, \( B(k) \) the absolute value of the magnetic field at a spatial scale \( 2\pi/k \), \( k \) the absolute value of the wavenumber, and \( k_{\|} \) the component of the wavenumber parallel to the relative velocity.

The condition for instability in the presence of rotation was obtained by Huppert (1968):

\[ k_{\|}^2 V_{\text{rel}}^2 \geq 4\Omega^2, \]

where \( \Omega \) is the angular velocity. As we shall see, this condition is satisfied with a wide margin, and therefore the growth rate given by equation (1) is appropriate here.

3 THE ASTROPHYSICAL SETTING CONSIDERED

We consider the case of a disk galaxy similar to the MW. We adopt parameters consistent with the observations of Ho et al. (2017), Ho, Martin, & Turner (2019), Martin et al. (2019), Ho & Martin (2020), Zabl et al. (2019), and the simulations of Trapp et al. (2022). We consider a cold CGM gas that at a galactic radius \( R = 40 \) kpc has approximately the same rotational velocity as that of the disk. We thus adopt a relative velocity which is radial (inward): \( V_{\text{rel}} = 40 \) km/s. At the galaxy outskirts we take \( \rho_1 = 1.67 \times 10^{-25} \) g cm\(^{-3} \) corresponding to a number density of 0.1 cm\(^{-3} \). The inflowing gas density at the above radius was taken to be \( \rho_2 = 0.055 \rho_1 = 0.2 \times 10^{-27} \) g cm\(^{-3} \). This yields \( \alpha_1 = 0.95, \alpha_2 = 0.05 \).

These parameters imply a mass accretion rate for an angular extension of the inflowing gas, \( 0 < \beta < 2\pi \), and a scale height \( H = 330 \) pc

\[ \dot{M} = 2\pi H \rho_2 V_{\text{rel}} \text{ M}_\odot \text{ yr}^{-1} \]

which is quite reasonable.

3.1 The vertical acceleration \( g \)

The vertical acceleration is the sum of the vertical components of the galactic acceleration and the self gravity of the disk:

\[ g = g_{\text{gal}} + g_{\text{self}}, \]

where \( g_{\text{gal}} = \frac{v_{\text{rotation}}^2 H}{R} \), and \( g_{\text{self}} = 2\pi G\Sigma \)

where \( \Sigma \) is the surface mass density of the disk. At \( R = 40 \) kpc we adopt the parameters from Sofue (2013): \( v_{\text{rotation}} = 158 \) km/s, and \( \Sigma = 1 \) M\(_\odot\) pc\(^{-2} \). These imply \( g_{\text{gal}} = 1.8 \times 10^{-11} \) cm s\(^{-2} \) and \( g_{\text{self}} = 8.8 \times 10^{-11} \) cm s\(^{-2} \), yielding \( g = 1.06 \times 10^{-10} \) cm s\(^{-2} \).

3.2 Random galactic magnetic field

Many observations were made with the aim of revealing the nature of the galactic random magnetic field. Rand & Kulkarni (1989), Ohno & Shibata (1993), Han, Ferriere, &Manchester (2004), and Han (2017) concluded that measurements of the rotation and dispersion measures of pulsars can be well represented by a random field with coherence length ("cell") \( L_B \) and field strength \( B_0 \). As a result, the average field along a given line of sight of length \( L = 2\pi/k \) due to the randomly oriented in-cell fields is

\[ B(k) = B_0 \left( \frac{k}{k_B} \right)^{2}, \quad k \leq k_B, \text{ where } k_B = \frac{2\pi}{L_B}. \]

Substituting this to equation (1) yields

\[ n_s = \sqrt{\alpha_1 \alpha_2 k^2_{\|} V_{\text{rel}}^2 - \frac{B_0^2}{2\pi(\rho_1 + \rho_2) k^2} - gk(\alpha_1 - \alpha_2)}. \]

We adopt \( B_0 = 1 \) \mu G and \( k_B = 2\pi/(200 \) pc). Substitution of the numerical values shows that \( n_s(k) \) is real and positive for wavenumbers \( 1.31 \times 10^{-22} \text{ cm}^{-1} < k < 8.51 \times 10^{-22} \text{ cm}^{-1} \) corresponding to spatial scales \( 0.24 \text{ kpc} < 2\pi/k < 15.5 \text{ kpc} \).

4 TURBULENCE MODEL

Extending the earlier turbulence models of Canuto & Goldman (1985) and Canuto, Goldman, & Chasnov (1987), we employ the model of Canuto, Goldman, & Mazzitelli (1996) to derive the expected power spectrum of the turbulence. The model is formulated as an integral equation which represents a balance between the net rate of energy input to the turbulence in the wavenumber range \( (k_0 - k) \) and the rate of the energy cascaded to all scales smaller than \( k \).

\[ \int_{k_0}^{k} n_s(k') dk' = y(k) \nu_1(k), \]

where \( y(k) = \int_{k_0}^{k} F(k') k'^2 dk' \).

\( F(k) \) is the power spectrum of the turbulent velocity, \( y(k) \) is the \( k \)-space mean square vorticity at wavenumber \( k \), \( n_s(k) \) is the net rate controlling the energy input from the source at \( k \) incorporating the rate of energy dissipation by molecular viscosity, and \( \nu_1(k) \) is the turbulent kinematic viscosity at wavenumber \( k \) exerted by all the eddies with wave number larger than \( k \). Here, \( k_0 \) is the wavenumber corresponding to the largest scale of the turbulence. The turbulent viscosity at wavenumber \( k \) is defined by

\[ \nu_1(k) = \int_{k}^{\infty} F(k') \nu_2(k') dk'. \]

Here, \( \nu_2(k) \) is the rate controlling the eddy nonlinear correlation (heuristically the rate of the eddy breakup at \( k \)).

By differentiating equation (7) it is possible to obtain a rate equation:

\[ n_s(k) + \frac{y(k)}{n_s(k)} = \nu_1(k) k^2 = \gamma n_s(k). \]

The second term on the left hand side is the rate controlling...
the energy cascaded from all spatial scales larger $2\pi/k$. The
right hand side is the rate at which energy is transferred to
the smaller scales, with $\gamma$ a positive dimensionless constant
which was fitted by Canuto, Goldman, & Mazzitelli (1996) to
produce a Kolmogorov inertial power spectrum, yielding $\gamma = 0.088 (K_c/1.5)^{-3}$. Here $K_c$ denotes the so-called Kolmogorov constant.

The eddy correlation rate is modeled as
\[ \gamma n_s(k) = \left(\left[\gamma n_c(k)\right]^{1/2} + \left[n_s(k)\right]^{1/2}\right)^2, \tag{11} \]
and is dependent on both the turbulent viscosity and on
$n_s(k)$. For a given $n_s(k)$, the solution of the coupled equations
yields the power spectrum $F(k)$. The largest spatial scale corre-
spending to the smallest wavenumber $k_0$ is obtained from
\[ \frac{d}{dk}\left(\frac{n_s(k)}{k^2}\right)_{k_0} = 0, \tag{12} \]
and at this scale $F(k_0) = 0$.

By combining equation (10) and (11), one obtains an algebraic expression of $y(k)$ in term of $n_s(k)$ and $n_c(k)$:
\[ y(k) = \gamma^{-1} (\gamma n_c(k) - n_s(k)) \left(\left[\gamma n_c(k)\right]^{1/2} + \left[n_s(k)\right]^{1/2}\right)^2. \tag{13} \]

Differentiating equation (9) gives
\[ F(k) = - \left(\left[\gamma n_c(k)\right]^{1/2} + \left[n_s(k)\right]^{1/2}\right)^2 \frac{d}{dk}\left(\frac{n_c(k)}{k^2}\right), \tag{14} \]
which upon using the relation $dy(k)/dk = F(k)k^2$ leads to
\[ \frac{dy(k)}{dk} = -k^2 \left(\left[\gamma n_c(k)\right]^{1/2} + \left[n_s(k)\right]^{1/2}\right)^2 \frac{d}{dk}\left(\frac{n_c(k)}{k^2}\right). \tag{15} \]

From equations (13) and (15) one obtains a first-order differential equation for $n_c(k)$. The initial condition is $\gamma n_c(k_0) = n_s(k_0)$. Once $n_c(k)$ has been solved, equation (14) determines $F(k)$.

5 COMPUTED POWER SPECTRUM AND THE TURBULENT VELOCITY

We take $n_s(k)$ to be the linear growth rate given by equation (6). As has been argued by Canuto, Goldman, & Mazzitelli (1996), the self-consistent formulation of the eddy correlation timescale effectively modifies the growth rate and makes it dependent also on the turbulence. We obtain the velocity power spectrum and the value of the turbulent velocity for two sets of parameters that are within the range suggested by the observations and simulations. It is of interest to identify which features are independent of the precise values of the parameters.

5.1 Parameters set 1

For the parameters listed in the previous sections, equation (12) yields
\[ k_0 = 1.96 \times 10^{-22} \text{ cm}^{-1} \text{ and } \tag{16} \]
\[ L_0 = 2\pi/k_0 = 10.4 \text{ kpc}. \]

The smallest scale $2\pi/k_f$ for which $n_s(k_f) = 0$ is 240 pc. Note that $L_0$, the largest scale of the turbulence, is about $2/3$ of the largest scale at which $n_s > 0$. The formal solution of the power spectrum for $k < k_0$ is negative and thus no turbulence exists in this range even though $n_s$ is positive there. The growth rate at $k = k_0$ is
\[ n_s(k_0) = 9.9 \times 10^{-17} \text{s}^{-1} = \frac{1}{3.3 \times 10^8 \text{ yr}}. \tag{17} \]

The growth rate $n_s(k)$ and the power spectrum $F(k)$ are shown in Fig. 1 and Fig. 2, respectively. The power spectrum rises from $F(k_0) = 0$, reaches a maximum at $k \simeq 3k_0$ corresponding to a spatial scale of $\simeq 3.3$ kpc and then declines with a logarithmic slope that changes from -1 to -1.2 as $k$ increases.

The turbulent velocity is
\[ v_{turb} = \sqrt{\int_{k_0}^{k_f} F(k)dk} = 32.6 \gamma^{-1/2} \text{ km/s}. \tag{18} \]

5.2 Parameters set 2

Here the computation is repeated for $V_{rel} = 80$ km/s, which
is at the high end of the observational and simulated values.
In order not to obtain an unrealistically high mass accretion rate, a lower value of $\rho_2$ is adopted; $\rho_2 = 3.06 \times 10^{-27}$ g cm$^{-3}$. Thus, $\alpha_1 = 0.982$ and $\alpha_2 = 0.018$. The mass accretion rate for these parameters is
\[ \dot{M} = 32 HR \rho_2 V_{rel} = 0.1 \beta M_\odot \text{ yr}^{-1}, \tag{19} \]

similar to that obtained for the previous parameter set. The largest turbulence scale is larger (reflecting the larger value of $V_{rel}$):
\[ k_{02} = 1.4 \times 10^{-22} \text{ cm}^{-1} \tag{20} \]
\[ L_{02} = 2\pi/k_{02} = 14.5 \text{ kpc}. \]

The smallest scale is 165 pc. Since the coherence length of
the power spectrum for these parameters is $22$ kpc in case 1. and
$14.5 - 0.20$ kpc for the parameters of case 2. It is zero for
the largest scale, rises and then declines, almost with a con-
stant logarithmic slope. For intermediate spatial scales the
power spectrum has a logarithmic slope of $-1.1$, which turns
gradually to a value of -2 for smaller scales.

6 DISCUSSION AND CONCLUSIONS

The power spectrum of the turbulence (Fig. 2 and Fig. 4) has a unique shape. It spans wavenumbers corresponding to
spatial scales in the range $((10.4 - 0.22)$ kpc in case 1. and
$(14.5 - 0.20)$ kpc for the parameters of case 2. It is zero for
the largest scale, rises and then declines, almost with a con-
stant logarithmic slope. For intermediate spatial scales the
power spectrum has a logarithmic slope of $-1.1$, which turns
gradually to a value of -2 for smaller scales.
While the regions where the power spectrum has a power-law dependence on the wavenumber resembles an inertial range, this not the case, since $n_s(k)$ is not zero in this range. Actually, the latter fact is the reason for the shallow decline of the power spectrum (compared to the Kolmogorov spectral logarithmic slope of $-5/3$). For $k$-values larger than the maximal $k$ (where the energy input vanishes) there may exist an inertial range proportional to $k^{-5/3}$ provided that the microscopic viscosity can be neglected.

The turbulent velocity is 32.6 $\gamma^{-1/2}$ km/s for case 1. and 46.5 $\gamma^{-1/2}$ km/s for case 2. For the value of $\gamma \simeq 0.9$ obtained by Canuto, Goldman, & Mazzitelli (1996) the turbulent velocities are quiet large. This is due to the wide range and slow decline of the power spectrum.

We note that the time scale $n_s(k)$ is shorter than the rotation period at $R = 40$ kpc. In addition, the timescales that characterize the turbulence: $n_s(k)$ and $n_e(k)$ are much shorter.

Obviously, the numerical values depend on the assumed radial velocity and on the value of $\rho_2$. The range of the spatial scales of the turbulence changes as well as the normalization of the power spectrum and the turbulent velocity. However, the unique shape of the power spectrum is unchanged, a feature that identifies the turbulence as KH.

Observation of a fluctuating velocity field at the outskirts of a galaxy having a large-scale power spectrum with the shape obtained here could serve as indirect observational evidence for gas accretion from the CGM.

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7 DATA AVAILABILITY

This is a theoretical paper. No specific data is analyzed.

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