ON THE ROLE OF VISCOUS TRANSPORT IN THE OXYGEN ABUNDANCE GRADIENT OVER EXTENDED GALACTIC DISKS

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Draft version July 30, 2012

ABSTRACT

Inspired by recent observations of radial abundance gradients in the extended HI disks of galaxies, we present a numerical model to address the role of viscous transport with regard to the oxygen distribution in extended galactic disks. The viscosity in our one-dimensional disk approximation is provided by turbulent motions of the interstellar medium. These motions mix oxygen and other metals throughout the gaseous component of the galaxy. Our model runs for 7-10 Gyr, with the galaxy attaining mass through infalling gas and forming stars based on the Schmidt-Kennicutt Law. Through supernovae, these stars enrich their neighborhood of the galaxy with oxygen. Our model shows that viscous transport alone cannot account for the observed abundance of oxygen past the boundary of star formation in sample galaxies. These results argue in favor of the existence of another mechanism for the transport of oxygen.

1. INTRODUCTION

The observed radial abundance gradients in NGC 7793 (Vlajić *et al.* 2011), NGC 300 (Vlajić *et al.* 2009), NGC 2915 (Werk *et al.* 2010), M83 (Bresolin *et al.* 2009), NGC 4625 (Goddard *et al.* 2011), and the galaxies studied in the HI Rouges Sample (Werk *et al.* 2011) show an unexpected abundance of oxygen at large radii. Each of these galaxies have [O]/[H] ratios in the HI disk which reach and maintain a relatively high value at large radii, pointing to the presence of oxygen in their extended disks. Galaxies acquire material either through the accretion of infalling gas from the intergalactic medium or through mergers with other galaxies. The metallicity of the infalling gas from which galaxies are assembled is much lower than the overall metallicities of the galaxies. Therefore we can assume that the oxygen present in a galaxy was produced either internally through supernovae or through galactic mergers. As seen in (Werk *et al.* 2011), flat oxygen abundances exist both in galaxies that have undergone mergers and in galaxies that have not. Therefore mergers, though distorting the morphology and metallicity of their recipient galaxies, cannot be the only mechanism influencing the [O]/[H] ratios of those galaxies.

Supernovae and the oxygen they produce originate in the dense inner parts of a disk galaxy, where star formation takes place. The Kennicutt-Schmidt Law governs the existence of star formation below a cuttoff radius; the supernovae only form below that radius.

A significant supernova rate can only occur inside an approximate radius of star formation as modeled by the Schmitt-Kennicutt Law. The oxygen produced by these supernovae therefore only occur in the inner disk of a galaxy. Because we interpret the observed velocity dispersion in the HI disk to be turbulent gaseous motions, we must account for the radial mixing of oxygen that this causes.

In this work, we simulate the evolution of the radial abundance gradient of model galaxies using a viscous approximation for the diffusion caused by turbulent gaseous motions. By using observed parameters to model the evolution of the radial abundance gradient, we determine whether viscous transport alone can explain the observed oxygen abundance in the extended disks of galaxies, or whether there are other mechanisms at work as well.

2. METHOD

Our model avoids the complexity of multidimensional modeling. It reduces a galaxy to one dimension, with variables modeled as functions in the radial direction. The model represents the whole of the galaxy as a set of concentric rings. Because the model is axiosymmetric about the galactic center, a small region around the galactic center itself cannot be modeled accurately, and is excluded.

We derived a viscous disk approximation to model the effect of turbulent motions of the HI disk, and added the effects of star formation and gas infall:

$$\frac{\partial \Sigma_H}{\partial r} = (\partial_t \Sigma)_\nu + I_H - \dot{\Sigma}_{*_H}$$

$$\frac{\partial \Sigma_O}{\partial r} = (\partial_t \Sigma)_\nu + I_O - \dot{\Sigma}_{*_O}$$

where $\dot{\Sigma}_H$ and $\dot{\Sigma}_O$ is the surface densities of hydrogen and oxygen gas, respectively, I_H and I_O are the infall rates of hydrogen and oxygen gas, respectively, and $\dot{\Sigma}_{*_H}$ and $\dot{\Sigma}_{*_O}$ are the star formation rates of hydrogen and oxygen gas, respectively.

The approximation is implemented in the form of a system of ordinary differential equations. The solution to the viscous disk equation is in both space and time, so we use a finite difference approximation to discretize it in space, over radius. This leaves us with a set of coupled Ordinary Differential Equations, for which we use a packaged solver, `vode` with `bdf`.

This approximation utilizes a general form of the thin disk equation for the turbulent evolution of the gas disk over time. The viscous terms arise from these approximations and have the form:

$$(\partial_t \Sigma)_\nu = -\left(\frac{\partial}{\partial r} \left(\frac{\frac{1}{2\pi} \frac{\partial G}{\partial r}}{r\left(2\Omega + r\frac{\partial}{\partial r}\Omega\right)} \right) \right) \frac{1}{r}$$

where r is galactocentric radius, ν is the viscosity (as a function of radius), and Ω is the angular velocity, which is defined as $\Omega = V_\phi / r$, where V_ϕ is the rotational velocity. Following the results of (Thon and Meusinger 1998) we take it as sufficient to hold V_ϕ to be a "flat rotation curve" which does not change over time. The interstellar medium consists mostly of rarified, inviscid gas. It is the turbulent motions of the interstellar medium which diffuse angular momentum, causing torque.

To begin, the turbulent viscosity prescription is taken from the work of Klessen and Lin (2003), who present an extension of classical mixing theory into the supersonic regime.

$$D'(t) = 2\tilde{v}\tilde{t} \qquad \text{for } t \gg \tilde{l}/\tilde{v}$$

where $\tilde{v}$ is the root mean square flow velocity, $\tilde{l}$ is the typical shock travel distance, and t is a characteristic timescale. Klessen and Lin (2003) present this expression as an asymptotic limit for the rate of diffusion in the limit of long times $[t \gg l/v]$. We use this expression for the diffusion of momentum, which is more commonly referred to as viscosity ν.

$$\nu = D'(t)$$

The velocity dispersion of the HI component of the ISM can be directly measured with radio observations; we use this to set $\tilde{v}$. Based on Klessen and Lin (2003), we prescribe $\tilde{l}$ as the scale height of the interstellar medium, which is typically better known in the inner disk than in the extended disk.

The general form of the thin disk equation also accounts for gaseous infall over time. Galaxies tend to accumulate much of their mass from this gaseous infall, which gravitates out of the intergalactic medium. As in Thon and Meusinger (1998), the infall expression is given

$$I = \frac{I_0 \Sigma_0^i(R)}{t_i} e^{-t/t_i}$$

where I_0 is a free parameter which regulates the amount of infalling gas, $\Sigma_0^i(R)$ is a function describing the initial radial infall, and t_i is the characteristic timescale of the galactic infall. As with the viscous terms of the general equation, we use two different expressions to model infall: one for hydrogen, and one for oxygen. The two expressions have the same functional form, but the ratio between the two dictates the metallicity of the infalling gas.

Although significant oxygen abundances are observed in the entire gas disks of galaxies, oxygen is only produced within the inner disk, where star formation takes place. The rate of star formation can be approximated with the Kennicut-Schmidt law with an additional criteria for halting star formation in regions with insufficient gas. We use the Scalo initial mass function to specify the mass distribution of stars. The instant recycling approximation dictates that stars above a specific mass go supernovae, distributing oxygen into the galaxy. The expression:

$$\dot{\Sigma}_H = \dot{\Sigma}_{\text{total}} \left(\frac{\Sigma_H}{\Sigma_H + \Sigma_O} \right) \eta$$

gives the total mass of hydrogen expelled in supernovae due to star formation with units $[M_\odot pc^{-2} yr^{-1}]$, where $\dot{\Sigma}_{\text{total}}$ is the total mass of star formation, $\left(\Sigma_H/\Sigma_H + \Sigma_O\right)$ is the fraction of ejecta mass which is hydrogen, and η is the fraction of mass remaining after a supernova. By comparison, the expression

$$\dot{\Sigma}_O = \dot{\Sigma}_{\text{total}} \left(\frac{\Sigma_O}{\Sigma_H + \Sigma_O} \right) \eta \, + \, \dot{\Sigma}_{\text{total}} \beta \xi$$

gives the total mass of oxygen expelled in supernovae where β is the ejecta fraction and ξ is the calculated percentage of ejected material which is oxygen. We used the models of Woosley and Weaver (1995) to calculate ξ based on the Scalo IMF:

$$\phi(m) \propto \begin{cases} m^{-2.45} & (10M_\odot < m) \\ m^{-3.25} & (1M_\odot < m < 10M_\odot) \\ m^{-1.80} & (0.2M_\odot < m < 1M_\odot) \end{cases}$$

which describes the mass distribution of stars. In our model, some of the mass which goes into star formation eventually goes supernovae, producing oxygen proportional to the intake mass. Any stars with masses below that of $1M_\odot$ are assumed to have lifespans which exceed that of the simulation, so the mass used to produce them is essentially removed from our simulation.

3. RESULTS AND DISCUSSION

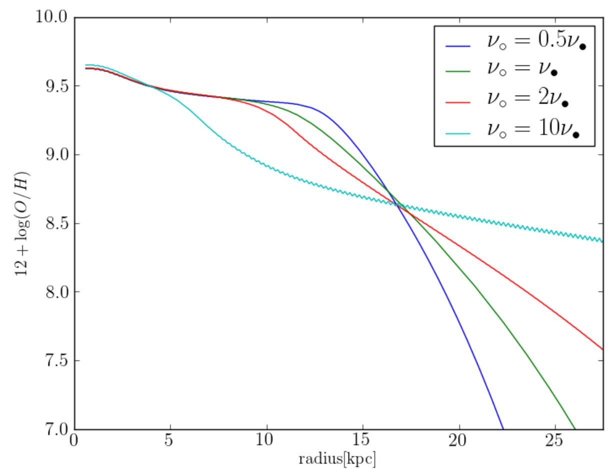

FIG. 1.— Radial Abundance Gradient

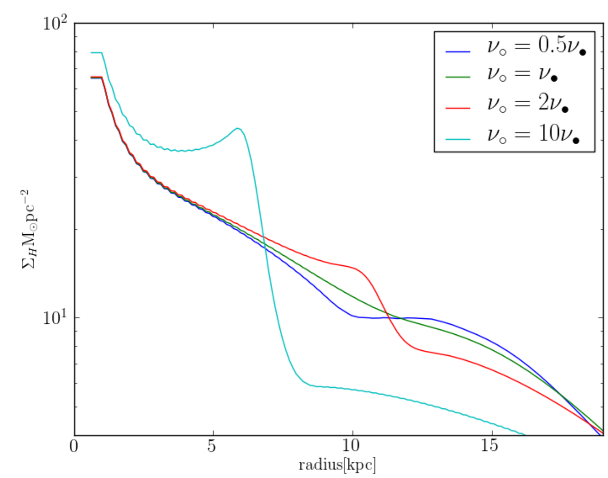

FIG. 2.— Σ_H

Because the oxygen yield derived from Woosley and Weaver (1995) is only an approximation of the true integrated

TABLE 1
MASS OF THE TOTAL GALAXY, GAS COMPONENTS, AND STAR REMNANT COMPONENTS OF EACH VISCOSITY TRIAL.

$\nu_\bullet/\nu_\circ$	final mass$_{\text{Total}}$	final mass$_{\text{gas}}$	final remnant mass
0.5	4.47E10 $M_\odot$	1.45E10 $M_\odot$	3.02E10 $M_\odot$
1	4.47E10 $M_\odot$	1.5E10 $M_\odot$	2.97E10 $M_\odot$
2	4.47E10 $M_\odot$	1.54E10 $M_\odot$	2.93E10 $M_\odot$
10	4.48E10 $M_\odot$	1.56E10 $M_\odot$	2.92E10 $M_\odot$

oxygen yield, trials run with $xi = 0.00747$ as the oxygen ejecta fraction often result in levels of oxygen in excess of the observed mass-metallicity trend for galaxies. To keep models and the graphs realistic, we derived $\xi' = 0.3\xi$. This coefficient of 0.3 restores oxygen abundance in the model to observed levels.

In a 1.0×10^{10} year simulation with 400 points between 1×10^3 pc and 5×10^4 pc, we ran four simulations with variable viscosity curves. Our initial parameters were:

$$\Sigma_0^i = 5 \times 10^2 \left[M_\odot pc^{-2}\right]$$
$$\mathrm{r_{char}} = 5 \times 10^3$$
$$\mathrm{t_{char}} = 6 \times 10^9$$
$$\xi' = 0.3\xi = (0.3)(0.00747)$$

We did four separate trials with variable viscosity curves. The viscosity component $\nu_\circ$, for the inner disk of the galaxy, where stars are present, is set at a constant $2.1 \times 10^{-3}\ pc^2\ yr^{-1}$, derived from a root mean square flow velocity of $\tilde{v} = 10\ km/s$ and a typical shock travel distance of $\tilde{l} = 10\ pc$. The viscosity component $\nu_\bullet$ for the extended disk, however, varies from trial to trial. From these trials we can obtain graphs of both the Radial Abundance Gradient ($12 + \log O/H$) and the Hydrogen Density Σ_H with respect to radius, measured in kiloparsecs.

A default case trial with a constant viscosity ($\nu_\bullet = \nu_\circ$) assumed that the inner and extended disk have the same turbulent properties. Another trial ($\nu_\circ = 0.5\nu_\bullet$) presents a case in which turbulence in the extended disk is not as effective in mixing the HI disk as it is in the inner disk. As can be seen in **Figure 1**, this case clearly does not aid radial oxygen transport, so we present a third trial ($\nu_\circ = 2\nu_\bullet$). It is reasonable to propose a larger viscosity in the extended disk than in the inner disk because of the turbulent viscosity proscription presented earlier by Klessen & Lin, which expresses viscosity as a function of length scale $\tilde{l}$. Because of the relative thickness of the extended disk, the length scale of the diffusion coefficient could easily lead to a larger viscosity in the extended disk. Similarly, a fourth trial ($\nu_\circ = 10\nu_\bullet$) has an extreme case of larger viscosity in the extended disk, encouraging the outward mixing of oxygen. However, because of the high coefficient, this trial causes gas to accrete in the center much faster, leading to a significant gas surface density dropoff at the edge of the inner disk, as seen in **Figure 2**. While this viscosity parameter gives a possibly realistic $[O]/[H]$ gradient in the extended disk, the surface density has a precipitous, unrealistic drop between the inner and extended disk due to the high efficiency of the viscosity in the extended disk.

Experimenting with different viscosity curves, it becomes apparent that there exists no compromise between a realistic hydrogen density and a realistic oxygen abundance gradient under the current assumptions of our model. With a large viscosity in the extended disk, the oxygen abundance resembles observed levels, but the hydrogen density becomes unrealistic. With a low viscosity in the extended disk, the radial hydrogen density is realistic, but there is no flat radial abundance gradient. The only compromise, a flatter radial viscosity curve, presents neither the desired flat oxygen abundance gradient nor a realistic hydrogen density curve. As a result, we can conclude that our model cannot account for the observed properties of the HI disks of galaxies by means of existing mechanisms, and that there must be an unknown mechanism at work.

4. CONCLUSION

Working from observed radial abundance gradients in the extended HI disks of galaxies, we offer a numerical model to address the role of viscous transport as the main mechanism with regard to oxygen distribution in extended galactic disks. Given the assumptions of our model, including a one-dimensional viscous disk approximation provided by a turbulent interstellar medium, an approximation for the value of the oxygen ejecta fraction, and models of turbulent diffusion and gas infall, we were unable to elevate the oxygen abundance in the extended disks of galaxies to the extent at which it is observed. Because our model is generous in many respects, it demonstrates effectively that viscous transport alone cannot account for the observed abundance of oxygen in the extended disks of galaxies. Our results therefore argue in favor of another ubiquitous mechanism for the transport of oxygen.

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