On The Origin of HI in Galaxies: Photodissociation and the “Schmidt Law” for Global Star Formation

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Abstract. Young stars in the disks of galaxies produce HI from their parent H₂ clouds by photodissociation. This process is widespread in late-type galaxies, and follows the distribution of Far-UV photons produced primarily by B-type stars. An estimate of the amount of dissociated gas can be made using observed Far-UV fluxes and simple approximations for the physics of photodissociation. This leads to the startling conclusion that much, and perhaps even all, of the HI in galaxy disks can be produced in this way. This result offers a simple, but inverse, cause-effect explanation for the “Schmidt Law” of Global Star Formation in galaxies.

1. Introduction

Discussions on the subject of global star formation in galaxies (e.g. Kennicutt 1989, 1997, 1998; Martin & Kennicutt 2001) are usually based on observed correlations between measures of the gas surface density in galaxy disks and the star formation rate. An example of such a correlation diagram is shown in Figure 1a (left panel), which plots on the X-axis the mean surface brightness in the 21-cm line of HI for a sample of local-universe galaxies, and on the Y-axis the corresponding observed mean surface brightness at λ = 1500Å taken from one of the first extensive surveys of nearby galaxies in the Far-UV (the FAUST survey, Deharveng et al. 1994). Similar correlations appear if the data on the Y-axis is the mean Hα surface brightness of the galaxy, or if a measure of the contribution from molecular gas (from CO(1-0) millimeter line observations) is included on the X-axis (although this latter “correction” generally does not improve the degree of correlation, as was first noted by Deharveng et al.).

2. Cause, Effect, and the “Schmidt Law”

The conventional approach is to parametrize plots such as that shown in Figure 1a as a power law, following a suggestion by Schmidt (1959) who assumed that the volume density of young stars formed per unit time in the Galactic disk is proportional to some power of the local gas volume density. The same parametrization is usually assumed to apply to the observed surface densities in nearby galaxies (Kennicutt 1989). Many authors have taken up the challenge to determine the power law index for a variety of data sets and, some 38 years after Schmidt’s seminal paper, Kennicutt (1997) reported an accumulation of
Ronald J. Allen

Figure 1.  a) **Left Panel**: Data showing a correlation between average observed 21-cm line surface brightness (converted to “Hi mass surface density”) on the X-axis and the Far-UV surface brightness (taken as a measure of the formation rate of massive stars) on the Y-axis, from Deharveng et al. (1994). “Schmidt Law” fits are shown, with indexes of 1 (dashed line) and 0.6 (solid line). b) **Right Panel**: The data plotted with axes inverted so as to emphasize the explanation in terms of photodissociation. The solid curves are the models of Hi production in PDRs described briefly in the text, and are labelled with the proton volume densities of the parent GMCs. The Hi area filling factor is assumed to be 0.30 over the disk of the galaxy.

∼ 50 papers dealing with the specific index appropriate for the “Schmidt Law” in nearby galaxies. The existence of such correlations is widely assumed to be strong evidence that the original assumption by Schmidt is valid.

Inherent in nearly all discussions of this topic to date is another assumption, namely, that the quantity plotted on X-axis of Figure 1a is the *cause*, and the quantity plotted on the Y-axis is the *effect*. However, the mere existence of a correlation does not, of course, tell us which quantity is the cause and which is the effect; it only tells us that the two quantities are related. Some other assumptions are required to guide us in this matter; Schmidt’s assumption provides this guide. It is against this backdrop that many papers have been published discussing the global star formation rate in galaxies as a function of various other parameters (galaxy type, galactocentric distance, etc.), and the current picture of global instability in galaxy disks has been proposed as the root cause of the star formation activity (Kennicutt 1989).

My purpose here is to point out that Figure 1 admits another explanation, one that is simple, and for which the physics is well understood. It is well known that Far-UV photons are capable of dissociating H$_2$ molecules into Hi atoms in the ISM (Stecher & Williams 1967), and that this process creates Hi layers on the surfaces of Giant Molecular Clouds (GMCs) (e.g. Andersson & Wannier 1993). The dissociating photons are in the energy range of a few eV below 13.6 eV and, since these photons are not energetic enough to ionize the
On the Origin of H\textsubscript{i} in Galaxies

H\textsubscript{i}, they can travel over long distances in the ISM, eventually being absorbed by an H\textsubscript{2} molecule or a dust grain, or escaping the galaxy. What has perhaps not been adequately appreciated up to now is that the morphological signatures of photodissociated H\textsubscript{i} can be found on a wide range of scales from 1 pc to 1 kpc in the Galaxy and in nearby galaxies (Allen 2002).

Does this “PDR” explanation for H\textsubscript{i} in the ISM extend to whole galaxies, and is the available flux of Far-UV photons from the typical spiral galaxy in the local universe quantitatively sufficient to produce the entire H\textsubscript{i} content of the galaxy for a reasonable range of physical parameters?

3. An Alternative Explanation for the “Schmidt Law”

In Figure 1b, I have plotted the data from Deharveng et al. with the axes inverted. The solid curves are models of H\textsubscript{i} production by photodissociation using the analytic solution developed by Sternberg (1988) (see also Madden et al. 1993, Smith et al. 2000) for an H\textsubscript{i} area filling factor of 0.3 and for a typical range of GMC volume densities $n = n_1 + 2n_2$. It appears from these results that photodissociation is indeed capable of providing a simple explanation for the “Schmidt Law” in Figure 1a when we “invert” cause and effect, as in Figure 1b. It is also clear that the photodissociation picture can explain such correlations when the H\textalpha flux replaces the Far-UV.

A very rough, but direct, order-of-magnitude estimate can be done to confirm that the observed Far-UV flux provides enough photons to maintain the entire H\textsubscript{i} content of the galaxy. Consider the case of NGC 4152, an Sc galaxy at D $\approx$ 19.5 Mpc in Virgo. The FAUST Far-UV flux is $\approx$ 6.3 $\times$ 10$^{-14}$ ergs/cm$^2$/s/Å integrated over the galaxy image (this galaxy is just over 2′ in diameter, so the corresponding data point is roughly in the middle of Figure 1). Summing over wavelength from 900 - 1100 Å (and presuming the spectrum is flat from here to 1500 Å) the observed flux corresponds to about 1 photon/cm$^2$/s at earth, or $\approx$ 4 $\times$ 10$^{52}$ Far-UV photons/s at NGC 4152. What is the appropriate time scale? This will roughly be the reformation time scale on dust grains for the process 2H\textsubscript{i} $\rightarrow$ H\textsubscript{2} on grains, $t_{\text{form}} = (2nR_{\text{form}})^{-1} \approx 5 \times 10^8/n_2$ yr for the standard PDR model parameters of Kaufman et al. (1999). If we take a typical GMC volume density to be $n_2 \approx 5 - 50$ H\textsubscript{2} molecules cm$^{-3}$, the reformation time is typically 5 - 50 $\times$ 10$^6$ yr. The H\textsubscript{i} production rate by photodissociation in NGC 4152 then accounts for:

$$2 \times 0.15 \times f_i \times 4 \times 10^{52} \times 5(50) \times 10^6 \times 3.15 \times 10^7 \approx f_i \times 2(20) \times 10^{66} \text{H}\textsubscript{i} \text{ atoms;}$$

where the factor 2 comes in because there are 2 H\textsubscript{i} atoms produced by each Far-UV photon, the factor 0.15 is the dissociation probability (calculated from atomic physics and averaged over all UV absorptions, e.g. Draine & Bertoldi 1996), and $f_i$ is the fraction of the observed Far-UV flux which has been trapped in the galaxy and is effective in causing photodissociation.

NGC 4152 is observed to contain $\approx 2 \times 10^6 M_\odot$ of H\textsubscript{i} (Huchtmeier & Richter 1989), or 2.5 $\times$ 10$^{66}$ H\textsubscript{i} atoms. If a typical value for $f_i \approx 0.5$, then at least 40%, and perhaps all, of the H\textsubscript{i} present could be accounted for by photodissociation! This result is surprising; a more complete discussion will be presented elsewhere.
4. Conclusions

Correlations of the kind shown in Figure 1 can arise naturally from the disassociating action of Far-UV photons reacting back on the GMCs from which the young stars were recently formed. Schmidt’s hypothesis therefore remains a reasonable, but unsubstantiated, point of departure for discussions of the formation of stars out of the interstellar gas.

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