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The Warm Ionised Medium in Spiral Galaxies: A View from Above

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Abstract: The warm ionised medium (WIM), also referred to as diffuse ionised gas (DIG), contains most of the mass of interstellar medium in ionised form, contributing as much as 30% of the total atomic gas mass in the solar neighborhood. The advent of CCDs has enabled unprecedented study of this medium in external galaxies, probing a variety of environments. In particular, we can derive the morphology of the WIM, its distribution across disks, and the correlation with other Population I material. Spectroscopy of the WIM makes it possible to test various ionisation models. I will review here our current understanding of the properties of the WIM in spiral galaxies. A perhaps unexpected result is that the Hα emission from the WIM contributes about 40% of the total observed Hα luminosity from spirals. This places severe constraints on possible sources of ionisation, since only photoionisation by OB stars meets this requirement. Spectroscopic measurements of forbidden line strengths appear in reasonable agreement with photoionisation models. It is not yet clear if the Lyman continuum photons that ionise the WIM are mostly from OB stars located inside traditional HII regions, or from field OB stars.

Keywords: galaxies: Local Group, spiral — ISM: HII regions, bubbles — ultraviolet: stars

1 Introduction

Warm ionised medium (WIM), or diffuse ionised gas (DIG), is the dominant component of the ionised interstellar medium (ISM) in disk galaxies. While the Hα emission from this component is 10 to 1000 times fainter than for traditional HII regions, and the gas has low density ($n_{\rm e} \sim 0{\cdot}2$ cm^{-3}), its large volume filling factor and spatial extent imply that the mass of the WIM easily surpasses that contained in traditional HII regions or in the hot gas in the ISM. Understanding the heating and ionisation mechanism for the WIM is a major challenge to models of the ISM. In external galaxies we can determine the overall distribution and morphology of the WIM across galactic disks, its correlation with other ISM phases, and the variation in its properties with Hubble type and star formation rate. In addition, we can test ionisation models for the WIM through spectroscopy, and through determining the relation between WIM and ionising stars. In this paper we will review results for galaxies that are not edge-on; see Rand (1998, present issue p. 106) for results on edge-on systems.

2 Warm Ionised Medium in Disk Galaxies

Emission line imaging with CCDs on even modest-sized telescopes is an excellent method for studying the WIM in galaxies, provided care is taken in flat fielding and subtraction of continuum light. Imaging with Fabry–Perot systems is another fruitful observational approach, as discussed by Bland-Hawthorn & Jones (1998, present issue p. 44). Most imaging studies have focused on Hα, sometimes including [NII](6548+6583 Å), and on [SII](6716+6731 Å) emission lines (e.g. Walterbos & Braun 1992, 1994; Hoopes, Walterbos & Greenawalt et al. 1996; Ferguson et al. 1996a,b). The Hα intensity one observes is directly proportional to the emission measure (EM), the integral of the electron density *squared* along the line of sight. For ionised gas at 10,000 K, 1 Rayleigh $= 5{\cdot}6 \times 10^{-18}$ erg cm^{-2} s^{-1} arcsec^{-2} = $2{\cdot}8$ pc cm^{-6}. The WIM is too diffuse to obtain density information from the ratios of forbidden lines such as the [SII] doublet. Thus we have no direct probe of the electron density, and hence column density of ionised gas, in observations of external galaxies. For the Galactic WIM, this information does exist through observations of pulsar dispersion measurements (see e.g. Kulkarni & Heiles 1988 for a review).

We show an example of a deep Hα image for the nearby spiral M33 in Figure 1. The WIM is brightest in regions with a high surface density of bright HII regions, although sometimes WIM patches or filaments are located far away from traditional HII regions (see also Hunter & Gallagher 1990, 1992).

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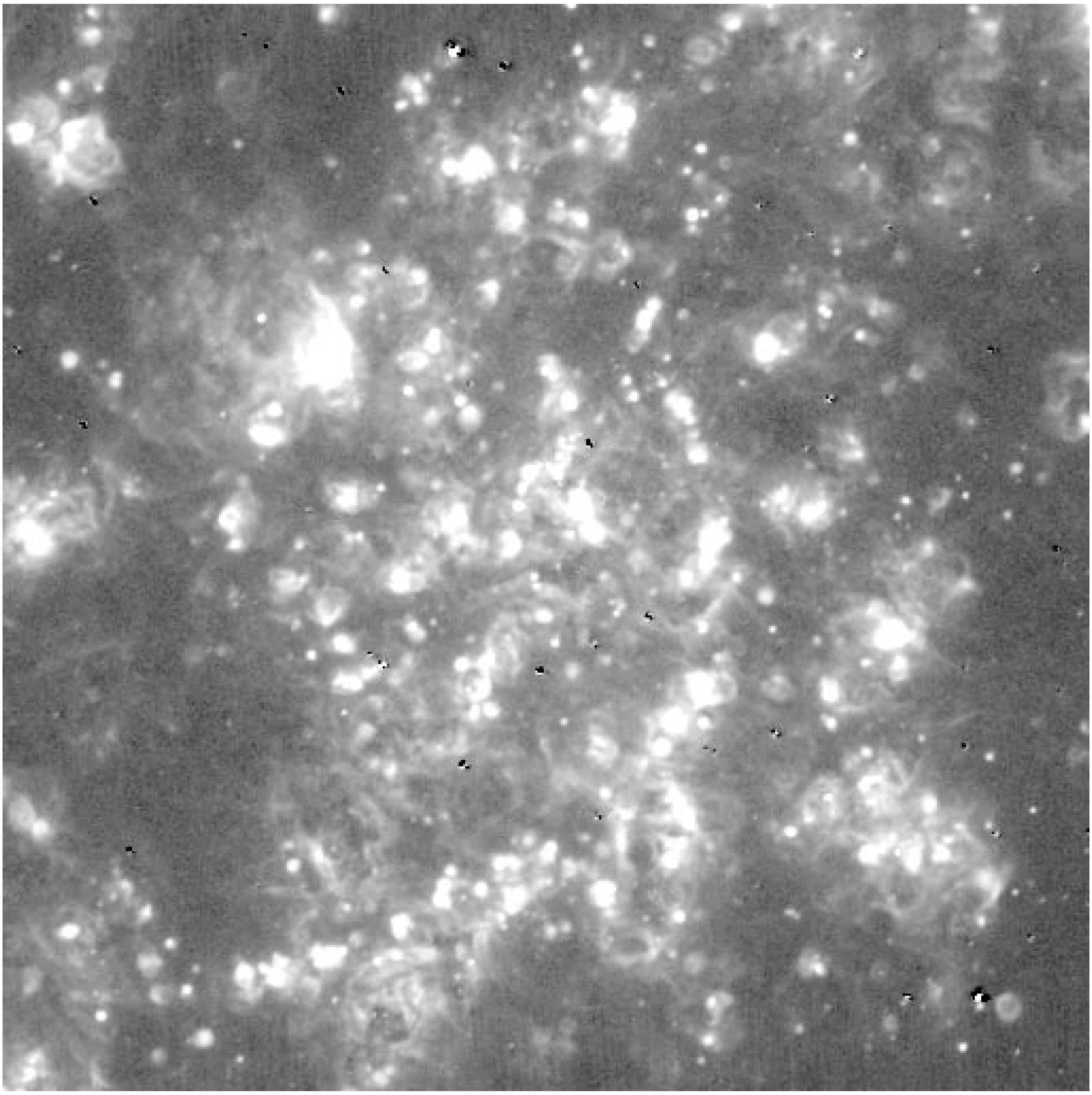

Figure 1—A 5-hour exposure in Hα+[NII] of the nearby spiral M33 obtained with the Burrell Schmidt telescope at Kitt Peak. The image shows the central 4·2 by 4·2 kpc^2. The brightest HII region in M33, NGC 604, is located just left and above the middle. The grey scale saturates at an EM of 500 pc cm^{-6}. Continuum light has been subtracted. The WIM seems to cover almost the entire area of the disk not occupied by traditional bright HII regions (from Greenawalt 1997).

The WIM covers a large fraction of the disk, here as much as 100%. Its morphology is a combination of diffuse emission and curved filaments, perhaps consistent with a 'dented sheet'. Typical emission measures contributed by the WIM reach up to as much as 50 pc cm^{-6} in spiral arms, down to as low as a few pc cm^{-6} at the faintest levels so far detected. For comparison, in the solar neighbourhood the Reynolds layer has an emission measure of about 5 pc cm^{-6} perpendicular through the disk.

Hα imaging allows straightforward determination of a crucial quantity: the *fractional* Hα luminosity contributed by the WIM in a galaxy. A detailed method on how to separate the WIM contribution from the total Hα luminosity has been described by Hoopes et al. (1996). Results are now available for M31 (Walterbos & Braun 1994), NGC 253, NGC 300 (Hoopes et al. 1996), NGC 247, NGC 7793 (Ferguson et al. 1996a), NGC 55 (Hoopes et al. 1996; Ferguson et al. 1996b), M81, M51, and M33 (Greenawalt 1997). A surprising result emerges: the contribution from DIG is 40±10%, irrespective of the star formation rate in all these galaxies. Such a result might be expected if the

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Hα emission we observe from the WIM were in fact scattered light from bright Hii regions in galaxies. However, the distinct spectral signature (see next section) and the distinct morphology of the WIM that is discernible in nearby galaxies (e.g. Walterbos & Braun 1994) make this unlikely. If the extinction is systematically less in the WIM compared to that in Hii regions, this number may be somewhat less. This has only been addressed for M31 (Walterbos & Braun 1994, Greenawalt, Walterbos & Braun 1997), where the corrected WIM fraction probably remains at least 20 to 30%. The high number for this fraction is relevant in that it forces us to accept that OB stars have to be the dominant ionisation mechanism. In addition, the fact that this fraction is constant among galaxies argues against a strong influence for an external ionising source. Instead, the constant fraction must be reflecting some fundamental property of the ISM and the distribution of ionising sources in galaxies. Either the medium is similarly porous in galaxies with widely different star formation rates per unit area, or the ratio of the number of *field* OB stars to the total number of OB stars is similar in all galaxies.

3 Spectroscopy of the WIM and the Source of Ionisation

The ionisation problem for the WIM has two aspects. First, the energy requirements to keep the medium ionised are enormous, leading to OB stars as the only viable candidates. But do photo ionisation models predict the correct spectrum for the WIM? Second, there is a transport problem, in that the mean free path for Lyman continuum photons in galactic disks is very small, typically less than a pc (this small number implied the existence of 'Strömgren spheres' in the ISM in the first place). So how can the ISM be ionised at large distances from OB stars? Do Lyman continuum photons leak from Hii regions, or are field OB stars responsible?

A characteristic of the Galactic WIM is its high [Sii] to Hα emission line intensity ratio (e.g. Reynolds 1988). The WIM in other galaxies shows the same behaviour (e.g. Walterbos & Braun 1992, 1994; Rand et al. 1990; Ferguson et al. 1996b, Hoopes et al. 1996). Spectroscopic results of Greenawalt et al. (1997; see Figure 2 here) for M31 and imaging results of Ferguson et al. for NGC 55 (1996*b*) show [Sii]/(Hα+[Nii]) to increase with decreasing Hα intensity. In M31, [Nii]/Hα and [Oiii]/Hβ do not change. These results agree with photoionisation models of Domgörgen & Mathis (1994) who calculated various line ratios for diffuse gas exposed to a strongly diluted radiation field. Overall, the WIM in M31 shows similar, but not identical, spectral characteristics as the Reynolds layer. The differences (e.g. stronger [Oiii]/Hβ in M31) indicate an overall less diluted radiation field in M31 compared to the solar neighbourhood, not surprising given that for M31 the relatively bright WIM in the spiral arms was observed.

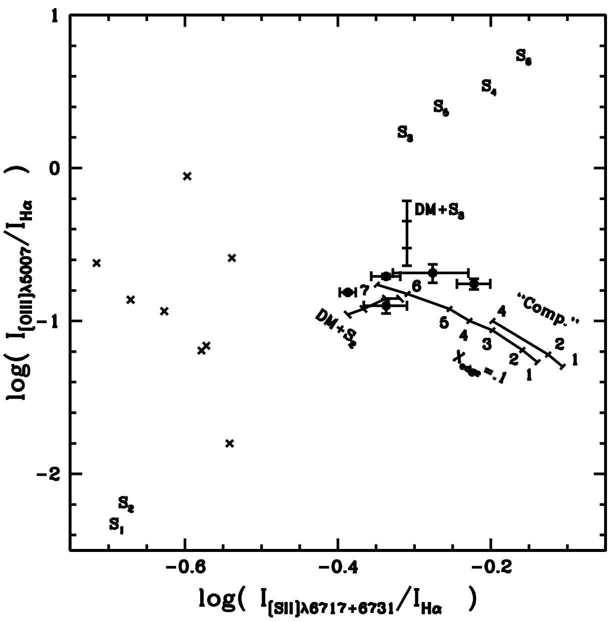

Figure 2—Line ratios for the WIM in M31 (filled dots) compared to various ionisation models. The crosses indicate bright Hii regions in M31. The lines indicate loci of photoionisation models from Domgörgen & Mathis (1994), for various diluted radiation fields. The 'S' points refer to mixing layers models (Slavin, Shull & Begelman 1993) for various temperatures and mixing speeds. The photoionisation models give satisfactory agreement and only a modest contribution from mixing layers appears to be allowed (from Greenawalt et al. 1997).

Ferguson et al. (1996) imaged NGC 55 in [Oii], detecting a smoothly increasing [Oii]/(Hα +[NII]) ratio with decreasing Hα intensity of the WIM. The WIM in M31 may show the same behaviour (Greenawalt et al. 1997). This trend appears not to be predicted in the photoionisation models of Domgörgen & Mathis (1994). Greenawalt et al. (1997) also looked at the predicted line ratios for mixing layer models (Slavin et al. 1993); it seems that a possible contribution from mixing layers to line emission from the WIM is less than 20%.

In distinguishing which spectral type of OB stars are playing a role in ionising the WIM, knowledge of the ionisation stage of helium is crucial, since only stars earlier than O8 can ionise helium in significant amounts. Early results for Galactic WIM at an average EM of 30 pc cm^{-6} (Reynolds & Tufte 1995) indicated that most of the helium in the direction they studied had to be neutral. This caused significant problems for photoionisation models, since not enough ionising radiation could be contributed by the late spectral type stars implied to be responsible for the ionisation of the WIM. More recently (see Reynolds 1998, present issue p. 14), the He(5876 Å) recombination line has been detected for Galactic WIM and in the halo gas of NGC891

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(Rand 1997), but it appears that He is not fully ionised. Greenawalt et al. (1997) concluded that for relatively bright WIM in M31 (at EM above 50 pc cm^{-6}), helium appears to be fully ionised. We could not derive information for WIM at lower intensity levels. It is clear that further measurements of the He recombination line are required in different environments.

4 Can Field OB Stars ionise the WIM?

Given that the WIM appears to be ionised by OB stars, do the Lyman continuum photons leak from HII regions, or are they due to field OB stars? The first possibility agrees with several characteristics of the WIM: an increase in forbidden line strengths compared to the Balmer lines towards lower Hα intensities, and the concentration of Hα emission from the WIM near HII regions. Ferguson et al. (1996a) argued that leakage has to occur because field OB stars may not contribute enough ionising photons. However, a careful census of the field star population is required. An O star in a low-density environment will have a large Strömgren sphere: about 150 pc for an O8 star in a medium with density $0 \cdot 2\ \mathrm{cm}^{-3}$, twice that for an O5 star. The concentration of OB field stars in the general areas near HII regions could well give rise to similar spectral characteristics for the WIM as the leaking HII region model. Elmegreen (1998, present issue p. 74) proposes a fractal HII region model, which implies that every OB star inside an HII region acts like a field OB star, a picture that would also account for the observed properties.

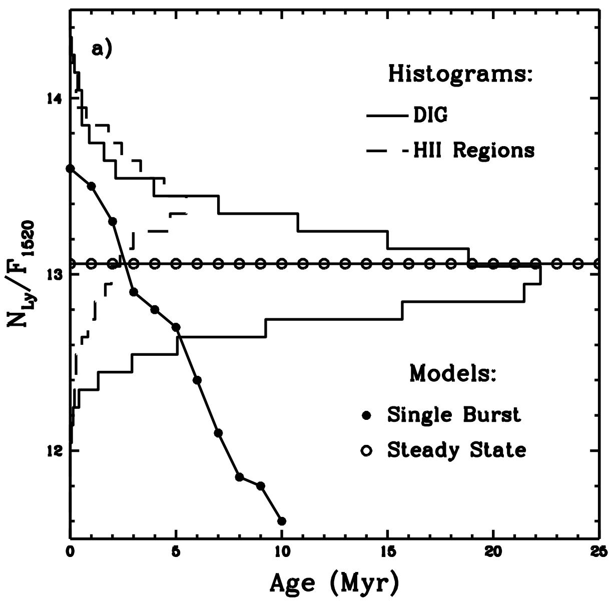

Figure 3—Ratio of the Lyman continuum to far-UV (1520 Å) luminosity in HII regions and DIG (= WIM) regions in M33, compared to models from Hill et al. (1995). The Lyman continuum luminosity is inferred from the Hα luminosity. The average ratio for the WIM appears consistent with that predicted for a steady state star formation rate (from Hoopes & Walterbos 1997).

We are addressing this problem by analysing far-UV images of the stellar light, obtained with the Ultraviolet Imaging Telescope on the ASTRO-1 and ASTRO-2 missions, in conjunction with the Hα images of the WIM. We test if the far-UV to Hα intensity ratios across galactic disks are consistent with those expected from luminous stars. An example is shown in Figure 3. The data appear consistent with ionisation of the WIM by field stars. However, there are several complications. Extinction effects are troublesome in analysing far-UV data. Some of the far-UV light in regions of WIM could be due to light scattered from OB stars inside HII regions. Also, while models such as those shown in Figure 3 predict sufficient Lyman continuum output to ionise the WIM, we need to determine if the *ionising* stars are actually present. We are doing this by analysing HST far-UV images of selected regions in nearby galaxies. Finally, the ionisation stage of helium is also critical in testing the viability of field stars as the source of ionisation.

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