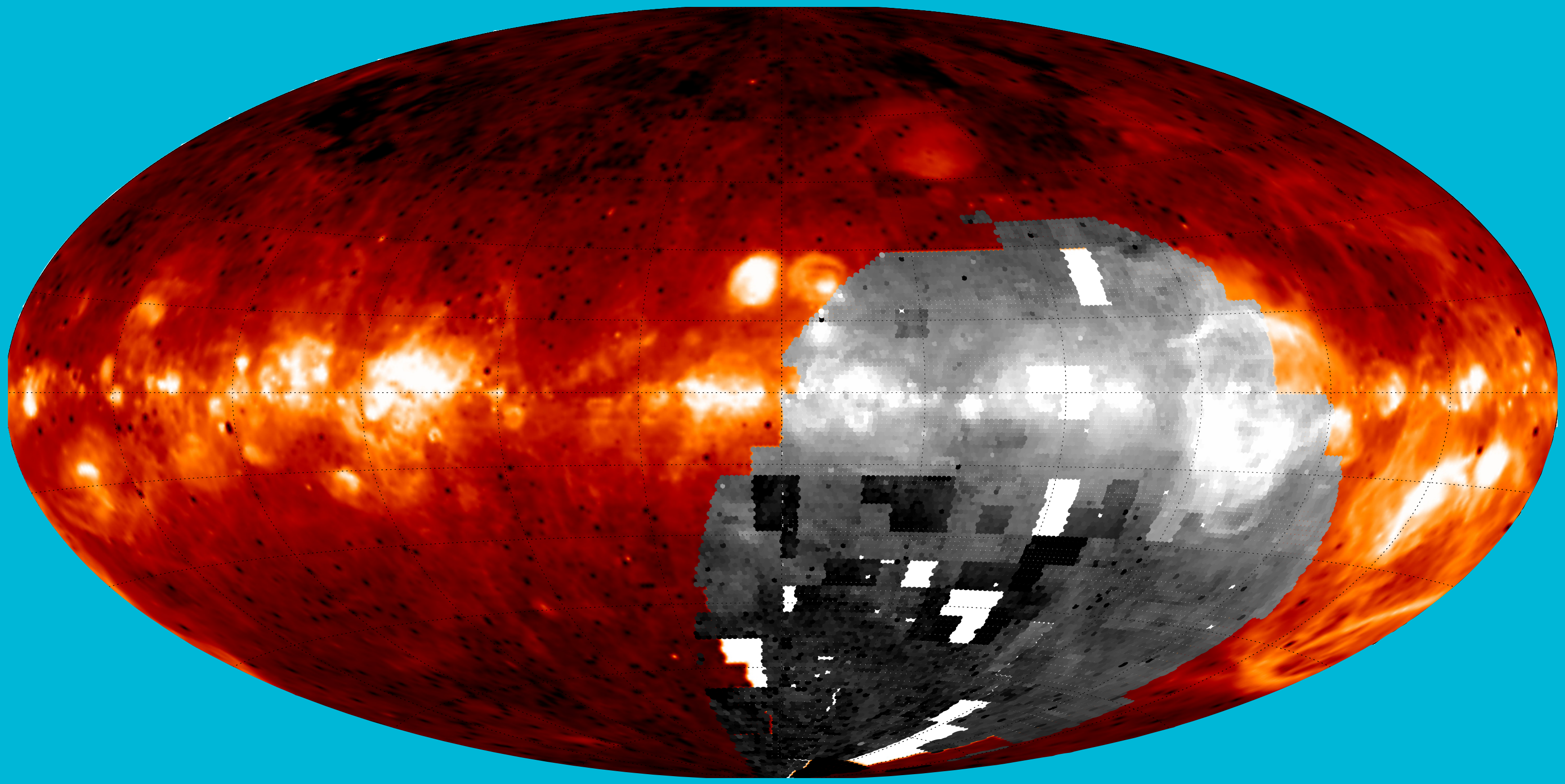

The warm ionised medium in the Milky Way

Alex S Hill

Matt Haffner, Ron Reynolds, & Kenny Wood

CSIRO ASTRONOMY & SPACE SCIENCE/AUSTRALIA TELESCOPE NATIONAL FACILITY
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ON THE EXISTENCE OF AN IONIZED LAYER ABOUT THE GALACTIC PLANE

By F. Hoyle* and G. R. A. Ellis†

[*Manuscript received November 8, 1962*]

Australian J. Phys.

Summary

The radio frequency spectrum observed in directions towards the galactic pole shows a maximum near 5 Mc/s. It seems unlikely that the synchrotron process responsible for the emission can give such a maximum and it is suggested that the observed fall in the flux density at lower frequencies is caused by absorption in an ionized layer parallel to the galactic plane.

To avoid an excessive value of the calculated electron density the kinetic temperature is taken as low as is consistent with the maintenance of ionization, about 10^4 °K. At this temperature the gas cannot fill the galactic halo but must form a layer along the galactic plane, the layer having a half-width of the order of 10^{21} cm. (~325 pc)

The electron density is found to be about $0 \cdot 1$ cm^{-3} so that along a line of sight to the galactic pole there are of the order of 10^{20} electrons. The mass of the layer is $\sim 5 \times 10^8 M_\odot$ and its rate of radiation in the Balmer continuum is $10^7 L_\odot$. The radiation rate per unit volume is $\sim 10^{-26}$ erg cm^{-3} s^{-1} in the Balmer continuum and the total radiation rate is $\sim 5 \times 10^{-26}$ erg cm^{-3} s^{-1}, a value close to the average emission of ionizing radiation by O and B stars.

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OBSERVATIONS OF DIFFUSE GALACTIC Hα AND [N II] EMISSION

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Received 1973 March 5; revised 1973 June 12

ABSTRACT

A study has been made of the intensities and radial velocities of faint galactic Hα and [N II] λ6584 emission lines not associated with any known bright H II regions. Although some (~10 percent) of the observed radiation may be scattered galactic light from bright H II regions in the galactic plane, most of the radiation appears to be produced by an ionized component of the interstellar gas which is distributed throughout the interstellar medium within the three nearby galactic spiral arms. In the local Orion arm the emitting gas has a temperature between 3000° and 8000° K and mean square electron density $\langle n_e^2\rangle \simeq 0.05\ \mathrm{cm}^{-6}$ in the galactic plane, while in the Perseus and Sagittarius arms $\langle n_e^2\rangle \simeq 0.1$ and $0.9\ \mathrm{cm}^{-6}$, respectively.

Subject heading: interstellar matter

CSIRO

Warm ionised medium (WIM)

Often called the "diffuse ionised gas" (DIG) or "Reynolds Layer"

Pervasive component of star-forming galaxies

≈90% of the H^+ and ≈1/4 of the total atomic H mass of the Milky Way ISM

Nearly fully ionised, $T = 6000 - 10000$ K

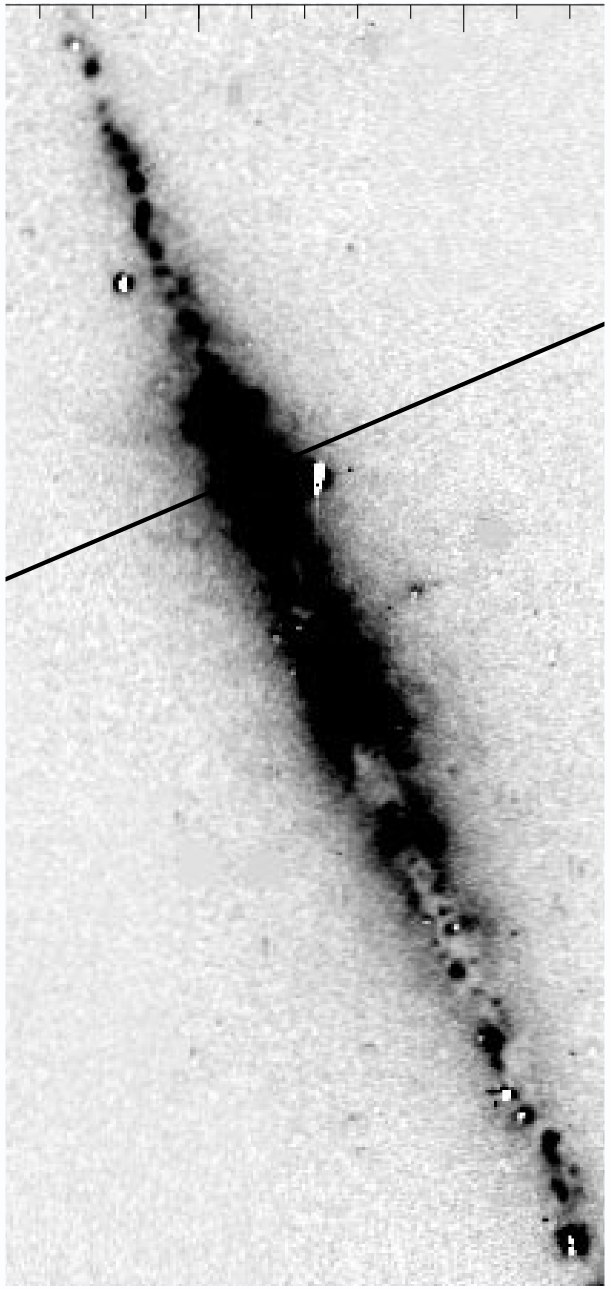
Extends to more than 1 kpc above the midplane

Observationally distinct from classical H II regions

Primarily photoionised by OB stars in the plane

- turbulent structure makes this possible

Haffner et al (2009 Rev Mod Phys)



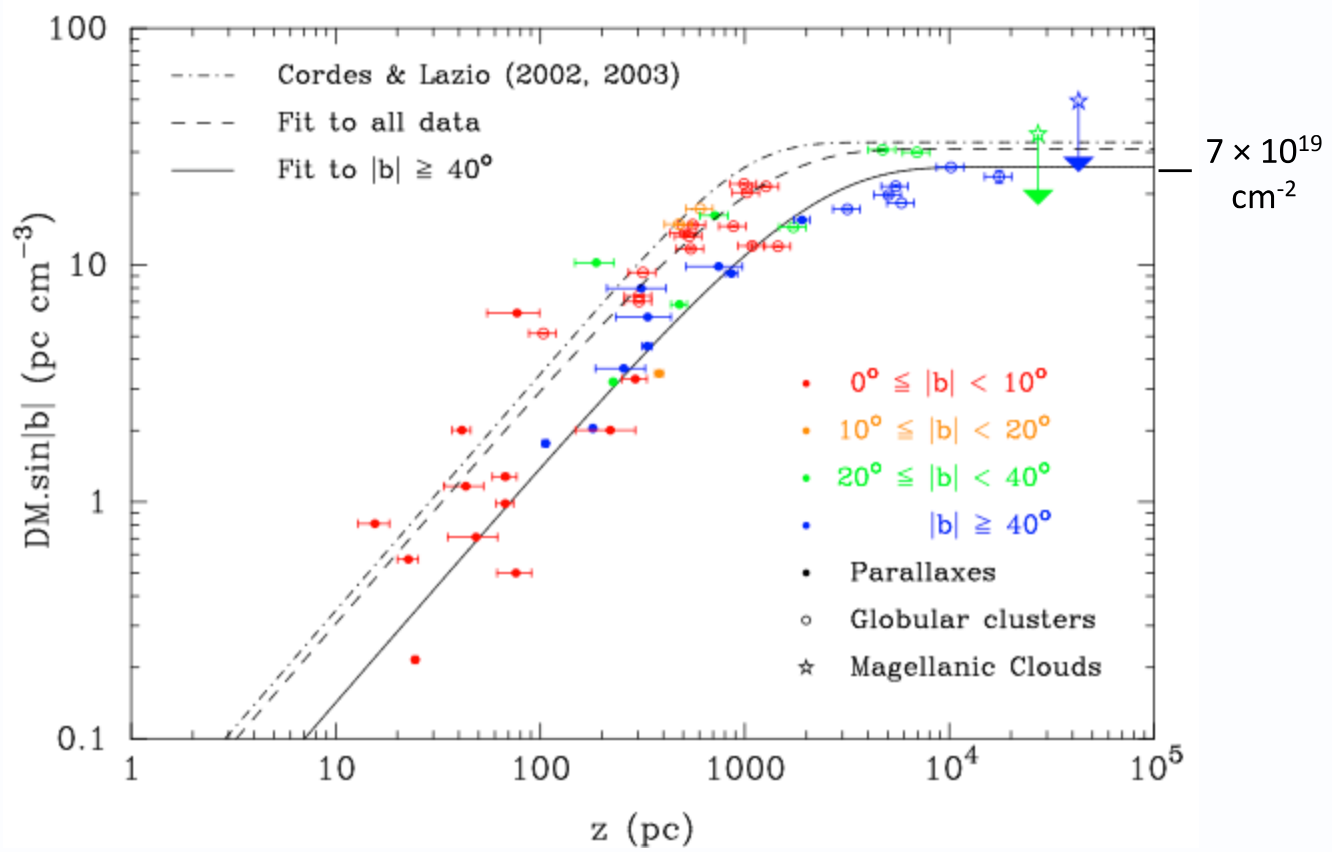
NGC 891
Rand et al (1990)

Observational evidence

Free-free absorption

Pulsar dispersion

- DM = $\int n_e \, ds \approx 7 \times 10^{19}$ cm^{-2} ⊥ to disk
  - ≈1/4 of total H column density
- Scale height
  - high-latitude pulsars: $1.41^{+0.26}_{-0.21}$ kpc (Savage & Wakker 2009 ApJ; see Gaensler et al 2008 PASA and Schnitzeler MNRAS in press, arXiv)
  - Al III: $0.90^{+0.62}_{-0.33}$ kpc (Savage & Wakker 2009)
  - Hα from Perseus arm: 1.0±0.1 kpc (Haffner et al 1999 ApJ)
- Space-averaged midplane density 0.02–0.03 cm^{-3}



Gaensler et al (2008 PASA)

Observational evidence

Free-free absorption

Pulsar dispersion

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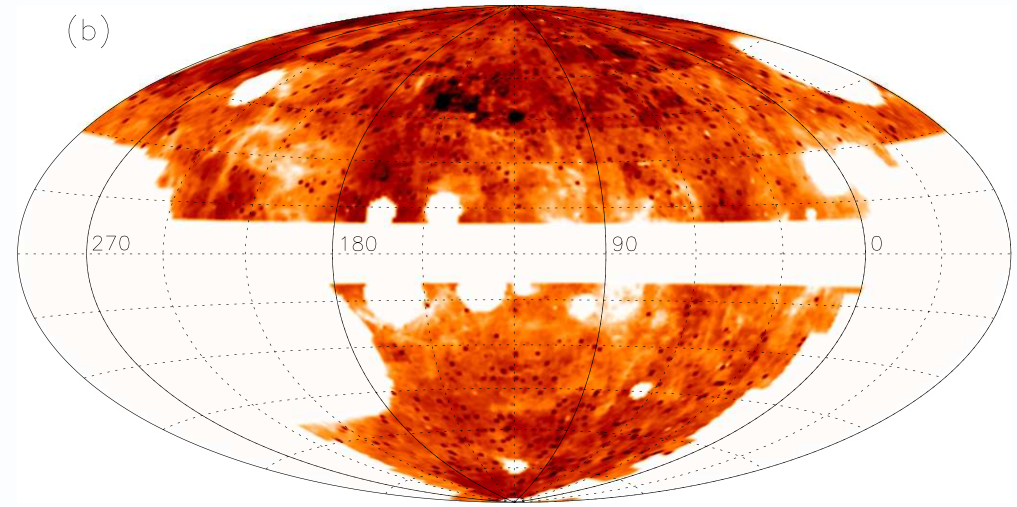
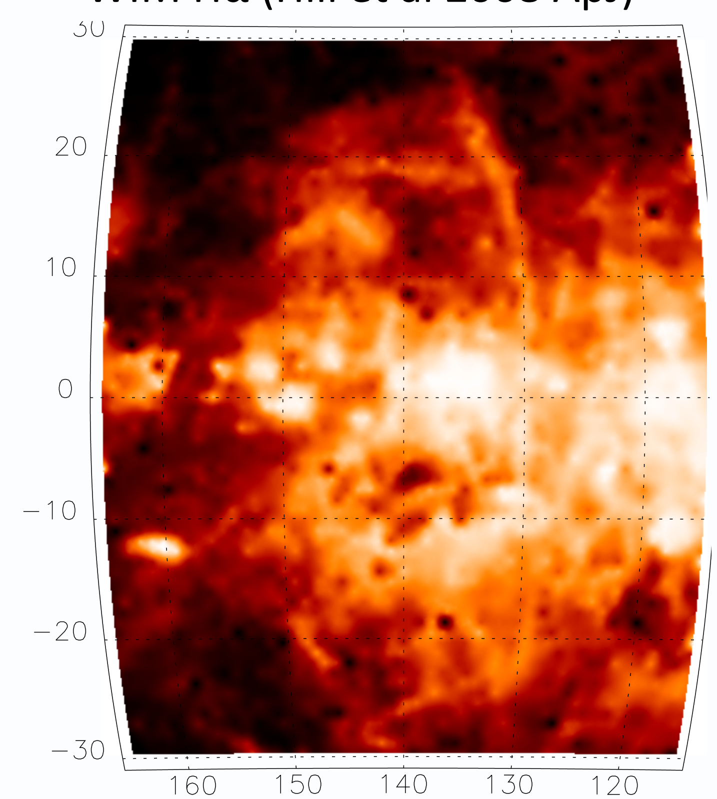
Hα emission

- $I_{H\alpha} \propto EM = \int n_e^2 \, ds$
- filling fraction 20 – 40% and may increase with height (Reynolds 1991; Gaensler et al 2008 PASA)
- density ≈0.05 – 0.1 cm^{-3} (Hill et al 2008 ApJ)



WIM Hα (Hill et al 2008 ApJ)



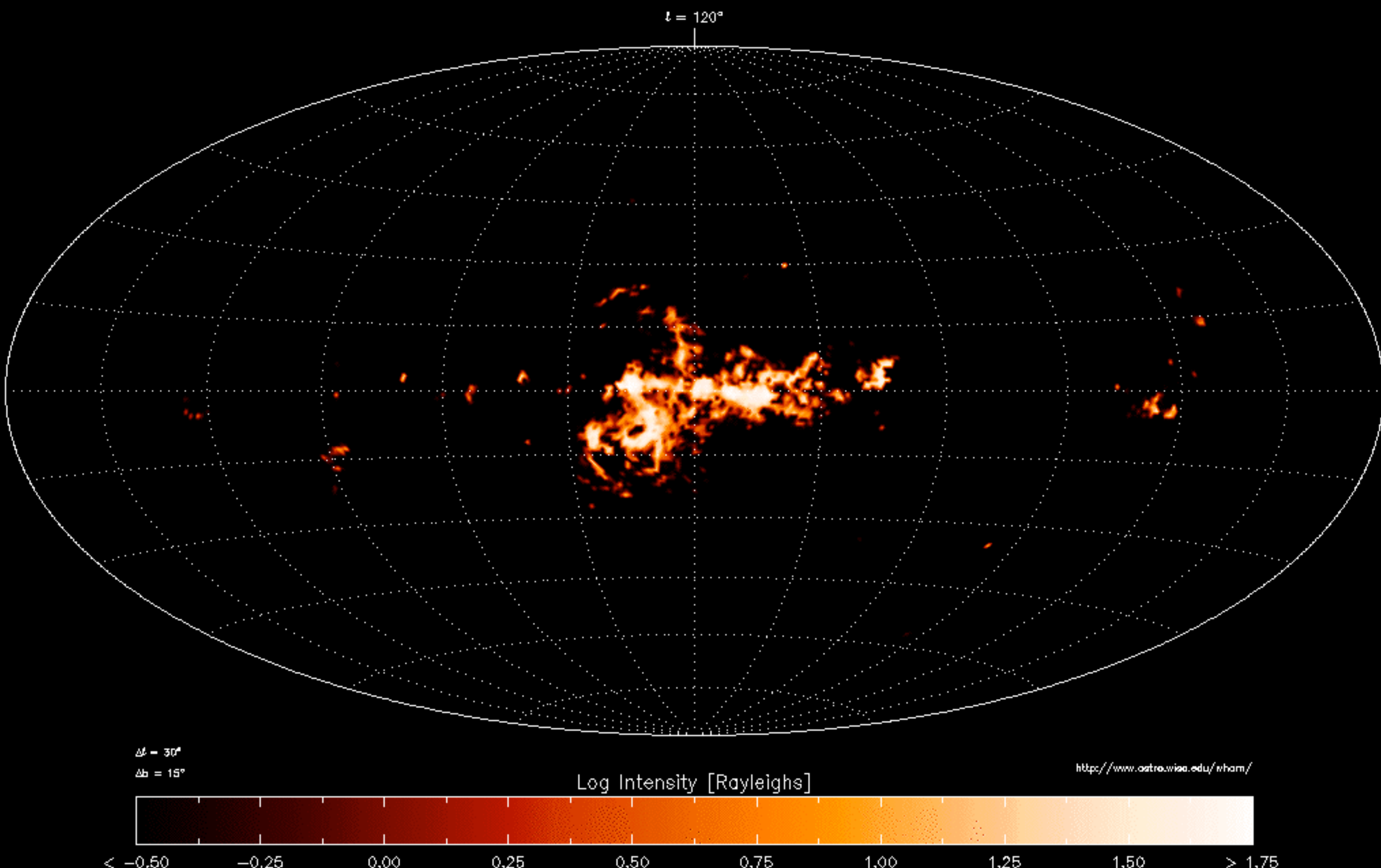
Perseus arm
Haffner et al (1999 ApJ)

WIM optical surveys

Survey	Sky coverage	Spectral resolution	Lines	Angular res	Sensitivity
WHAM-NSS (Haffner et al 2003 ApJS)	δ > -30°	12 km s^{-1}	Hα	1°	0.15 R
WHAM	partial	12 km s^{-1}	[N II] λ6584, [S II] λ6716, others 4800 A < λ < 7300 A	1°	<0.15 R
SHASSA (Gaustad et al 2001 PASP)	δ < +15°	imaging	Hα + [N II] contamination	0.8’	2 R
VTSS (Dennison et al 1998 PASP)	partial δ > -30°	imaging	Hα + [N II] contamination	1.6’	~1 R
Finkbeiner (2003 ApJS) composite of WHAM-NSS, SHASSA, and VTSS	Full	imaging	Hα + [N II] contamination	6’	Varies

Wisconsin H-Alpha Mapper Northern Sky Survey

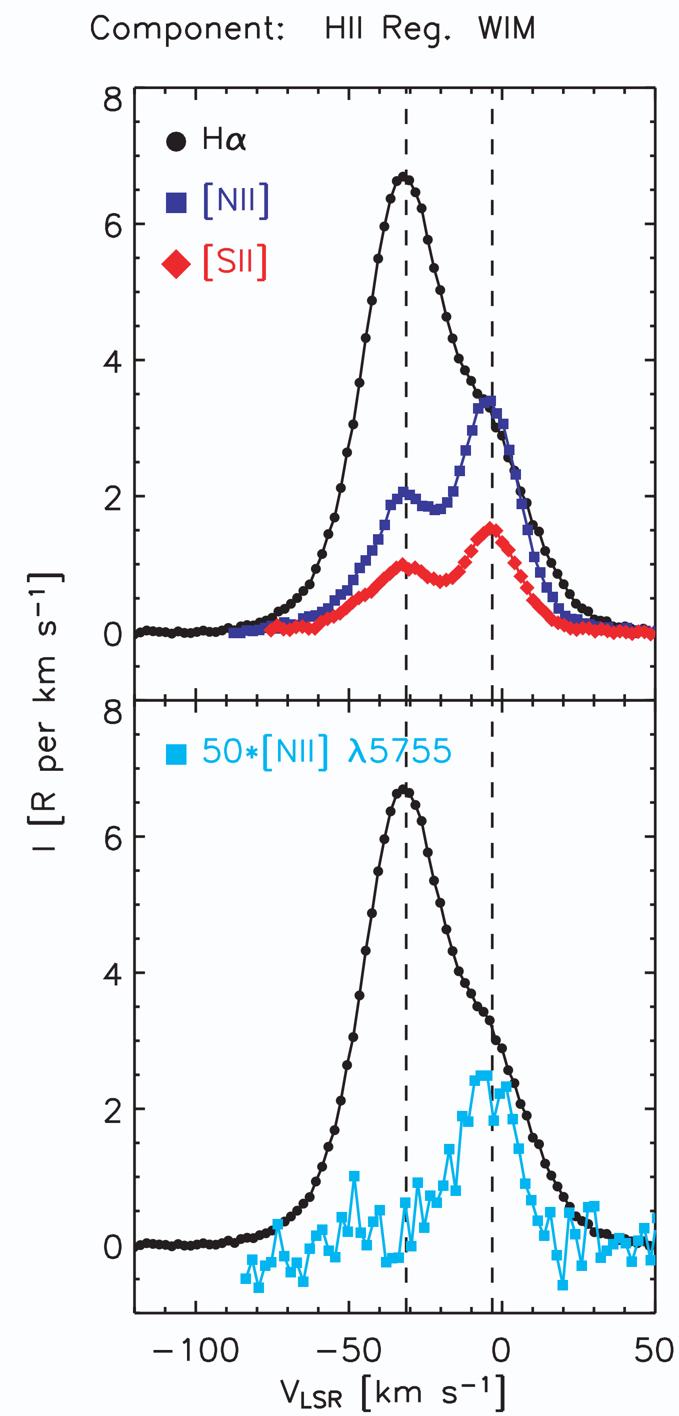
Integrated Intensity Map ($-82 < v_{LSR} < -77$ km s^{-1})



WIM Observations

Forbidden line emission

- Line ratios: WIM is distinct from locally-ionised classical H II regions (Reynolds 1985 ApJ)
  - Elevated [N II] / Hα and [S II] / Hα in WIM
    - WIM ~2000 K warmer than H II regions



Madsen, Reynolds, & Haffner (2006 ApJ)

Ionisation state

Forbidden line ratios probe temperature and physical conditions in the gas

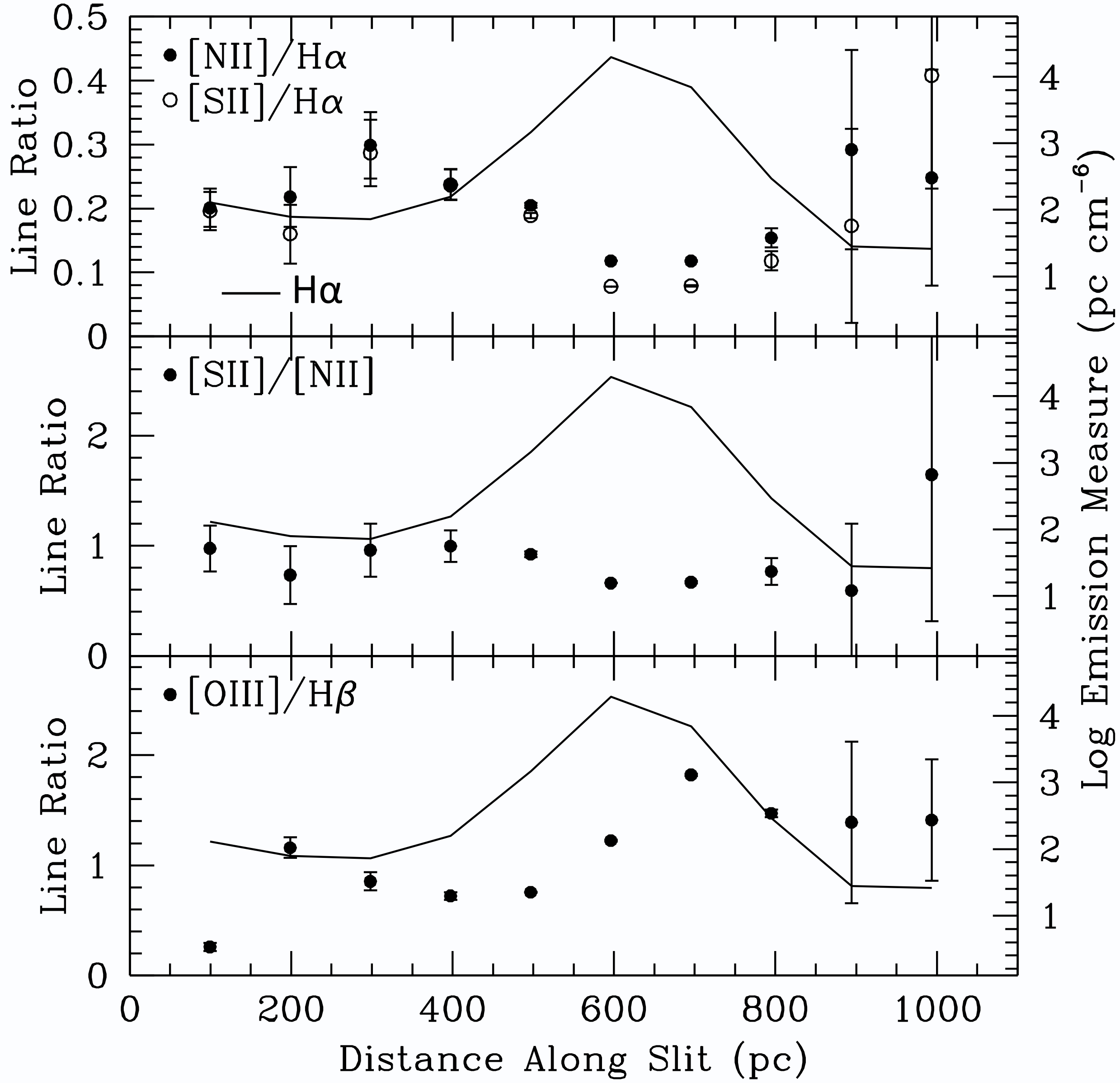
WIM Observations (Reynolds et al 1998 ApJ, Haffner et al 1999 ApJ, Madsen et al 2006 ApJ)

- [O I], [O III], and He I all very faint
- 0.1 ≲ [O II] / Hα ≲ 0.6 (Mierkiewicz et al 2006 ApJL)
- [S II] / Hα and [N II] / Hα are correlated with each other
- [S II] / [N II] relatively independent of Hα intensity

Conclusions

- He^0, O^+, N^+, and S^+ are dominant ions in WIM
  - O <–> H charge exchange: $H^+ / H \gtrsim 0.9$
  - Low ionisation parameter ($U \lesssim 10^{-3}$) (Mathis 1986 ApJ)
  - Deficit of He-ionising photons in WIM (Heiles et al 1996 ApJ; Hoopes & Walterbos 2003 ApJ)
- H II regions contain significant He^+, O^{++}, N^{++}, and S^{++}

NGC 604 in M33



Hoopes & Walterbos (2003 ApJ)

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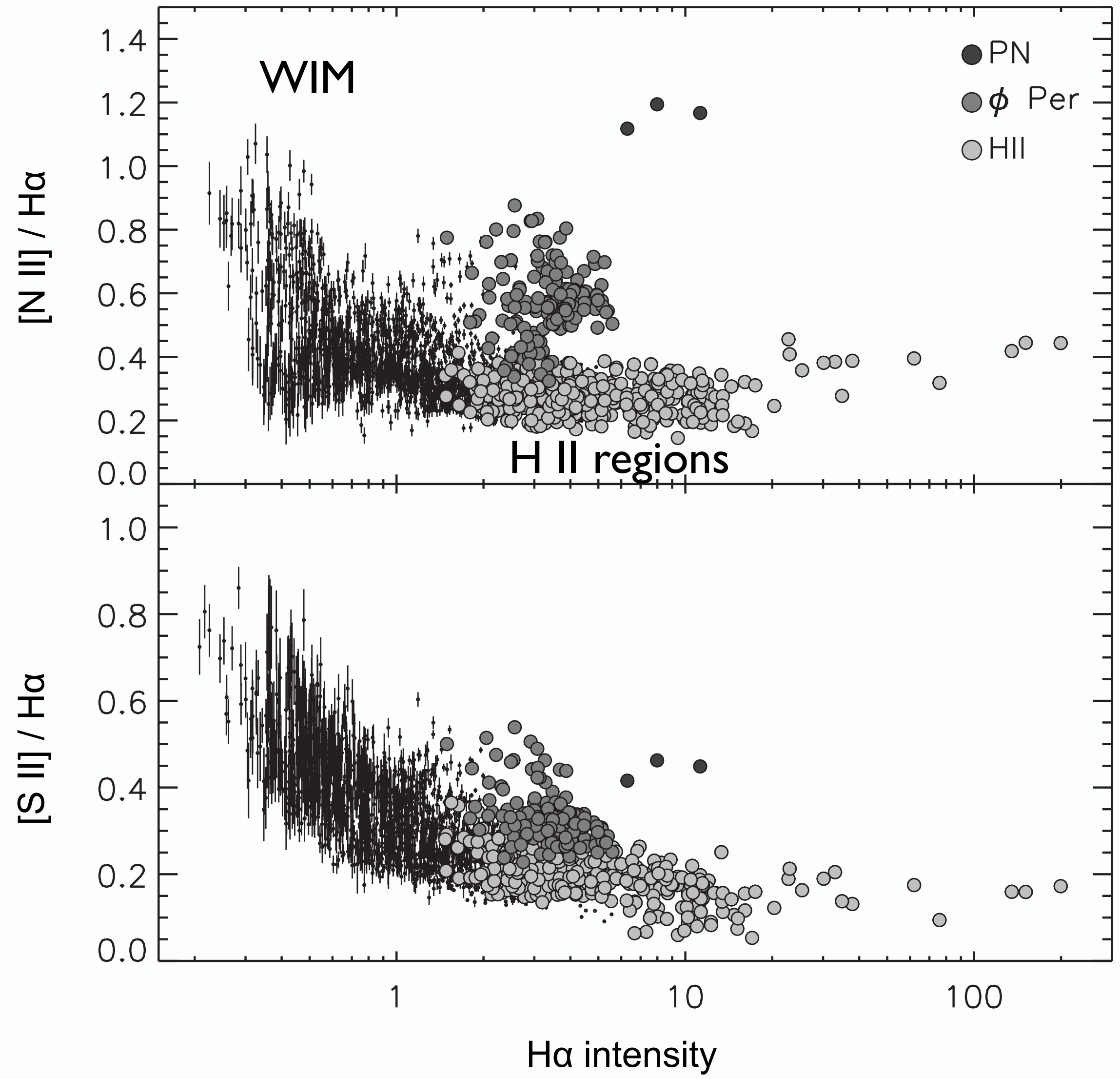

Haffner et al 2009 Rev Mod Phys

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Ionization Potentials (eV)		
Element	0→+	+ → ++
S	10.4	23.3
H	13.6	
O	13.6	35.1
N	14.5	29.6
He	24.6	54.4

Ionisation of the WIM

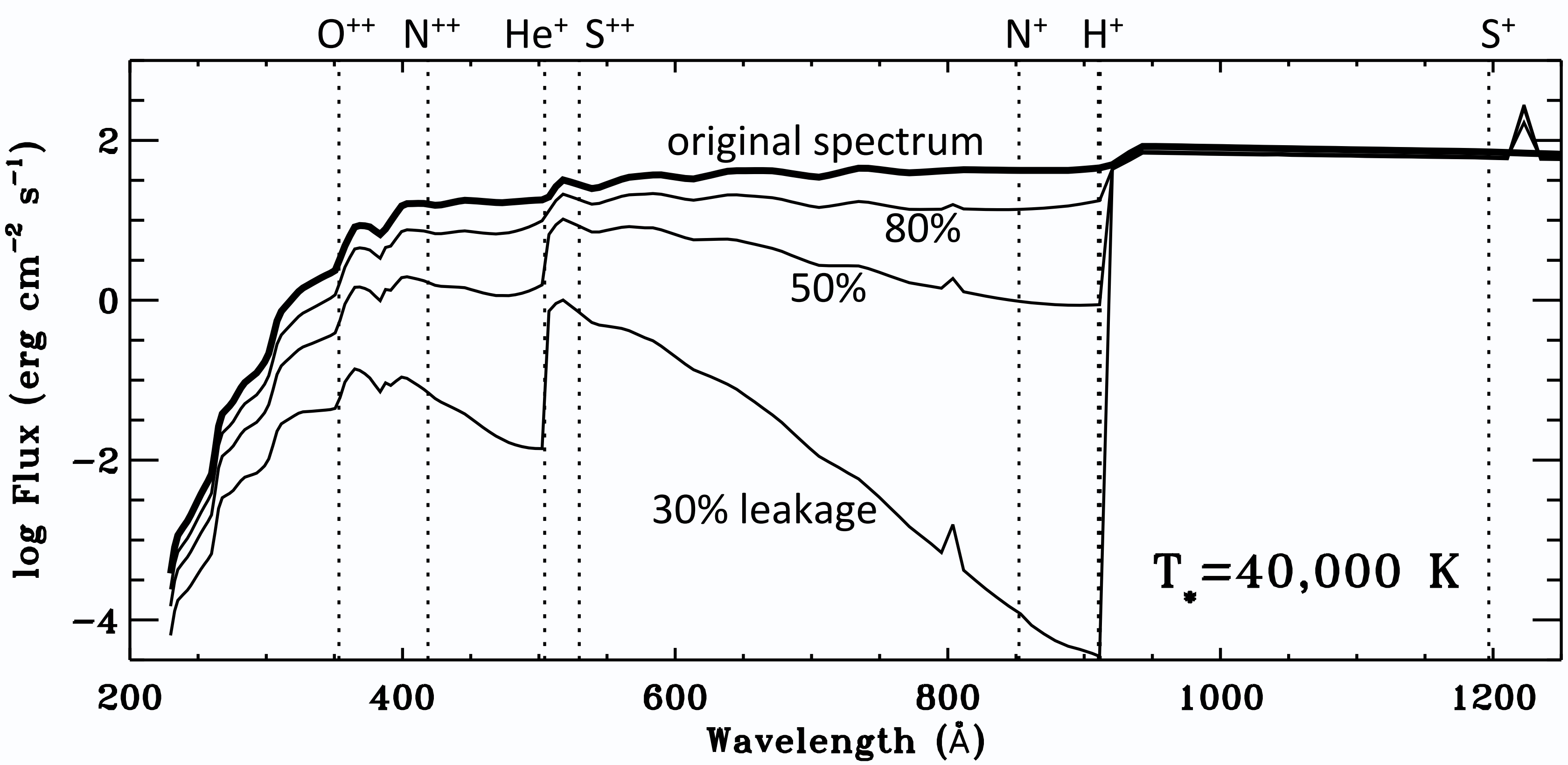
Ionising spectrum

Observations

- H^+, N^+, S^+, O^+, and He^0 are the dominant ions in WIM
- Significant N^{++}, S^{++}, O^{++}, and He^+ in H II regions

Modelling

- Requires harder spectrum with deficit of He-ionising photons in WIM
- Produced by ionising photons escaping from an H II region



Hoopes & Walterbos (2003 ApJ)

Ionisation of the WIM

Surface recombination rate of the WIM in the Milky Way

- 4×10^6 ionising photons s^{-1} cm^{-2} or $\approx 2 \times 10^{-4}$ ergs s^{-1} cm^{-2} (Reynolds 1990 ApJL)
  - about equal to kinetic energy input from supernovae
  - ≈1/7 of the Lyman continuum flux from OB stars
- How can ionising photons reach $|z| \sim 1$ kpc?
  - mean free path of ionising photon in $n \sim 1$ cm^{-3} WNM is ~0.1 pc

Photoionisation modeling

"Leaky" H II regions able to ionise WIM

- Smooth intercloud medium
- Lower-than-observed mean intercloud density required

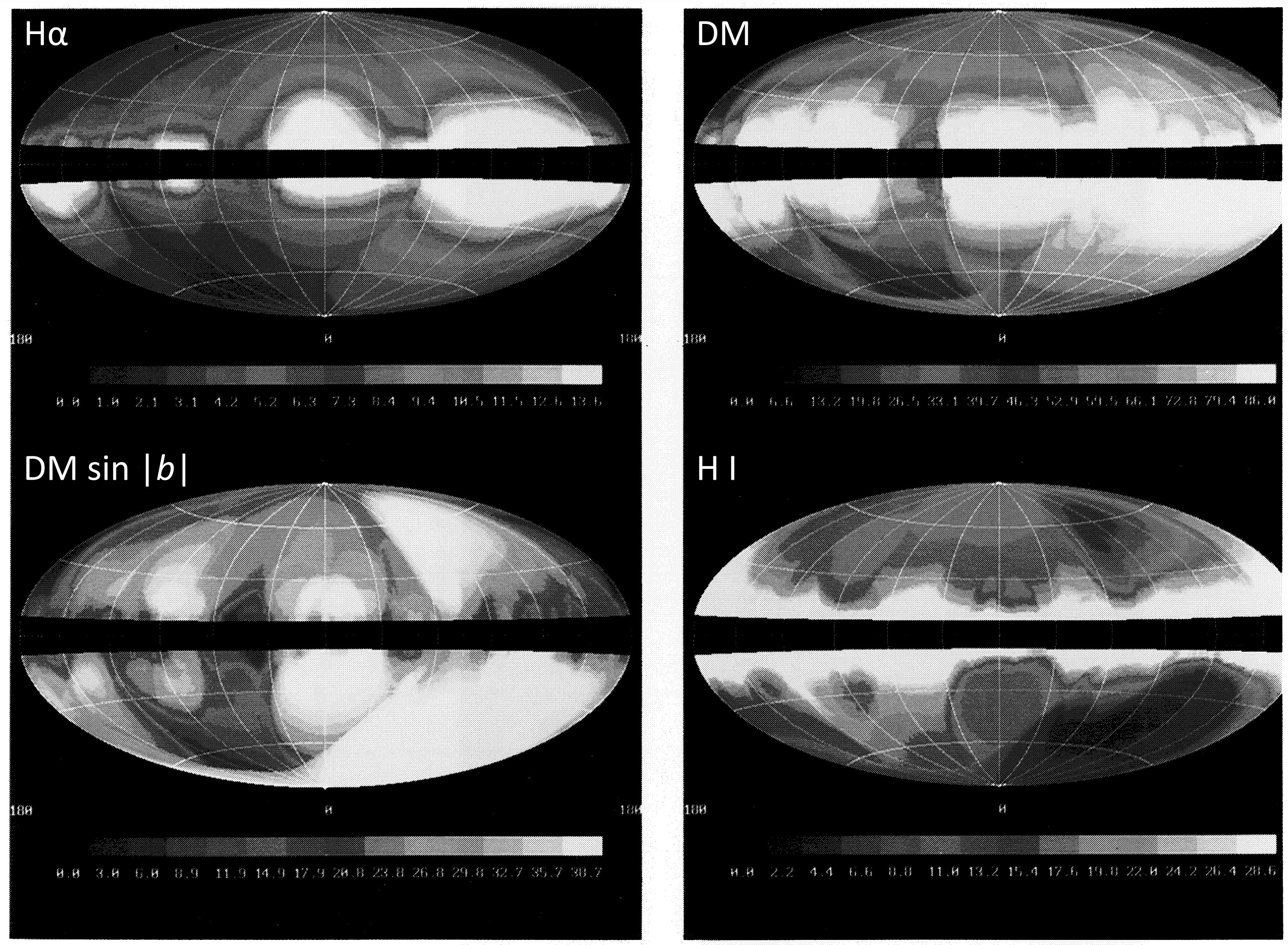


FIG. 12.—Aitoff projections from our standard cloud model of the (*upper left*) the emission measure (including ionized cloud faces), (*upper right*) the dispersion measure, (*lower left*) the vertical component of the dispersion measure (DM sin |*b*|), and (*lower right*) the residual neutral hydrogen column density. The projections are in Galactic coordinates (l, b) centered on $l = 0$ at 1° resolution. The scales are in units of cm^{-6} pc, cm^{-3} pc, cm^{-3} pc, and $cm^{-2} \times 10^{19}$, respectively. The quantities associated with each color bin represent upper limits to the bin of that color with the exception of the first bin (0.0 means truly 0.0) and the last bin (this bin contains everything greater than or equal to the bin label).

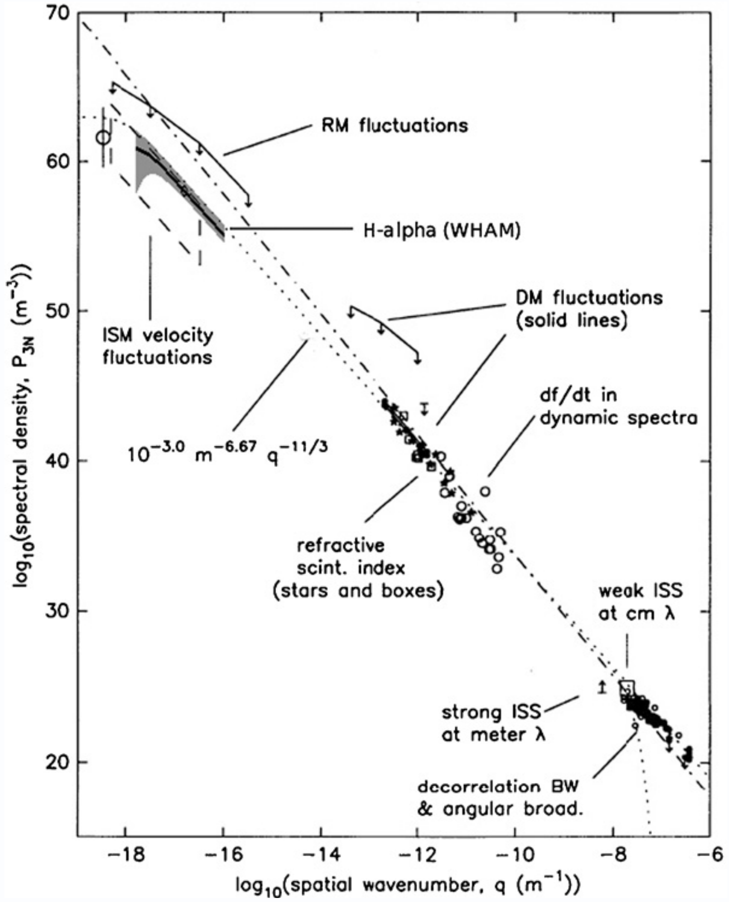
MILLER & COX (see 417, 586)

Miller & Cox (1993 ApJ)

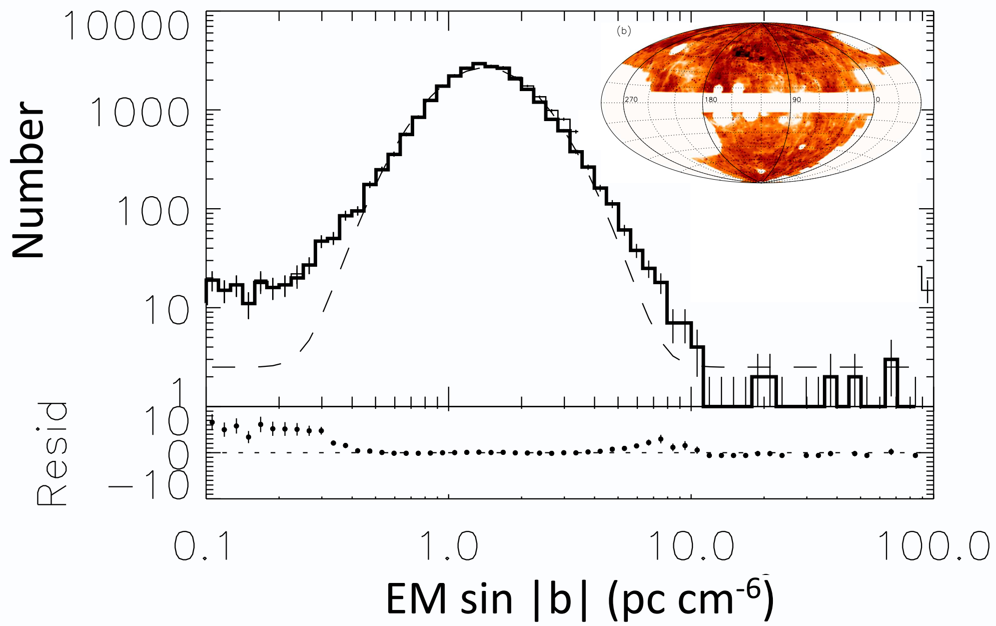
Turbulence

Variety of observations and theoretical expectations indicate that the WIM is turbulent (Rickett 1990 ARA&A, Benjamin 1999)

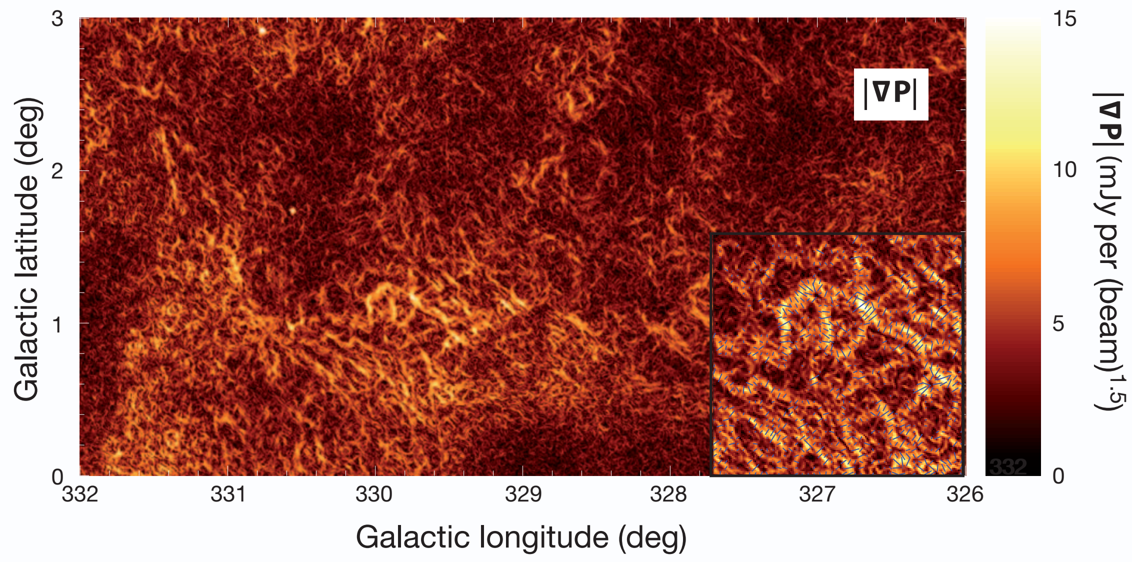
- Mach ~2 (Hill et al 2008 ApJ; Berkhuijsen & Fletcher 2008 MNRAS; Gaensler et al 2011 Nature; Burkhart et al 2012 ApJ)



Armstrong et al (1995 ApJ); Chepurnov & Lazarian (2010 ApJ)



WHAM data (Hill et al 2008)



Gaensler et al (2011 Nature); Burkhart et al (2012 ApJ)

Photoionisation in a fractal medium

Clumpy or fractal gas distribution allows ionising photons to penetrate to large heights (Elmegreen 1997 ApJ; Ciardi et al 2002 ApJ; Wood & Mathis 2004 MNRAS; Haffner et al 2009 Rev Mod Phys)

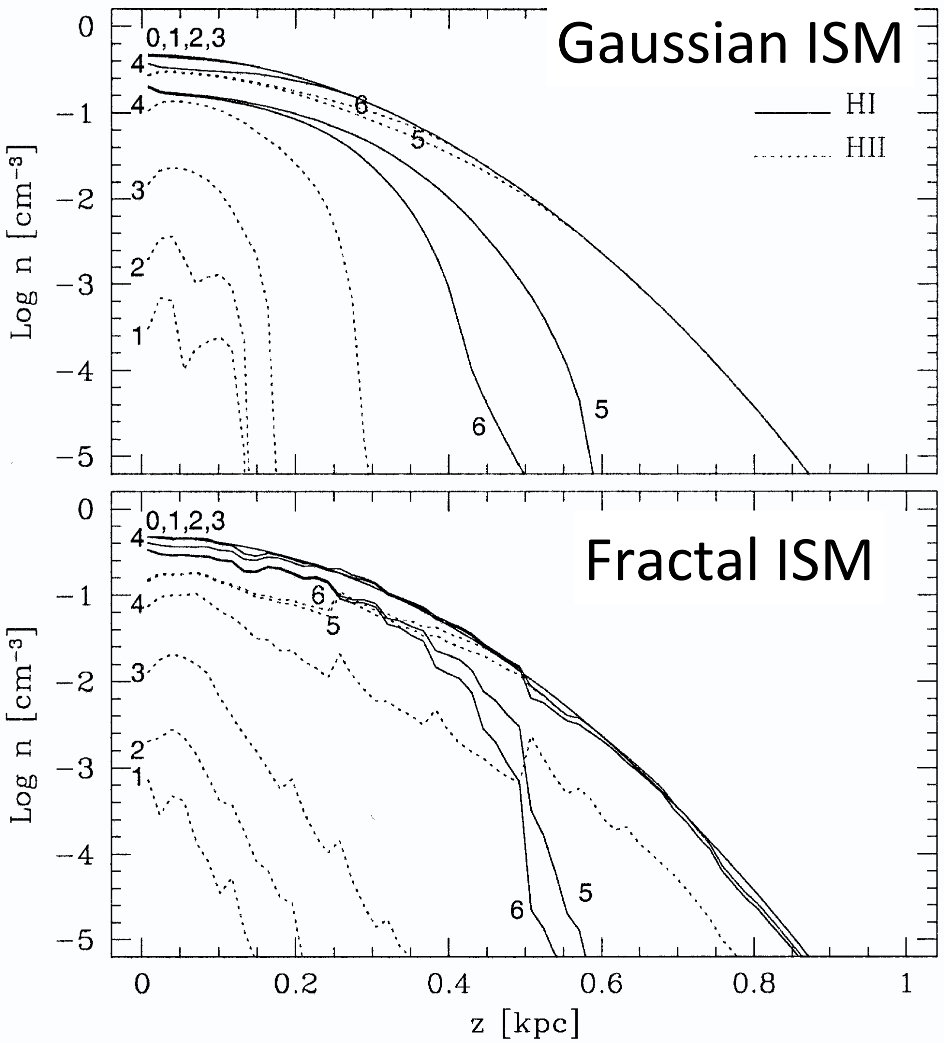


Figure 7. Vertical distribution of the mean H I (solid lines) and H II (dotted lines) number densities, in the case of a Gaussian (top panel) and fractal (bottom panel) density field. The numbers refer to different times from the source turn on: $i = 0\ldots6$ refers, respectively, to $t = 0$, 10^2, 10^3, 10^4, 10^5, 10^6 and 10^7 yr.

Ciardi, Bianchi, & Ferrara et al (2002 ApJ)

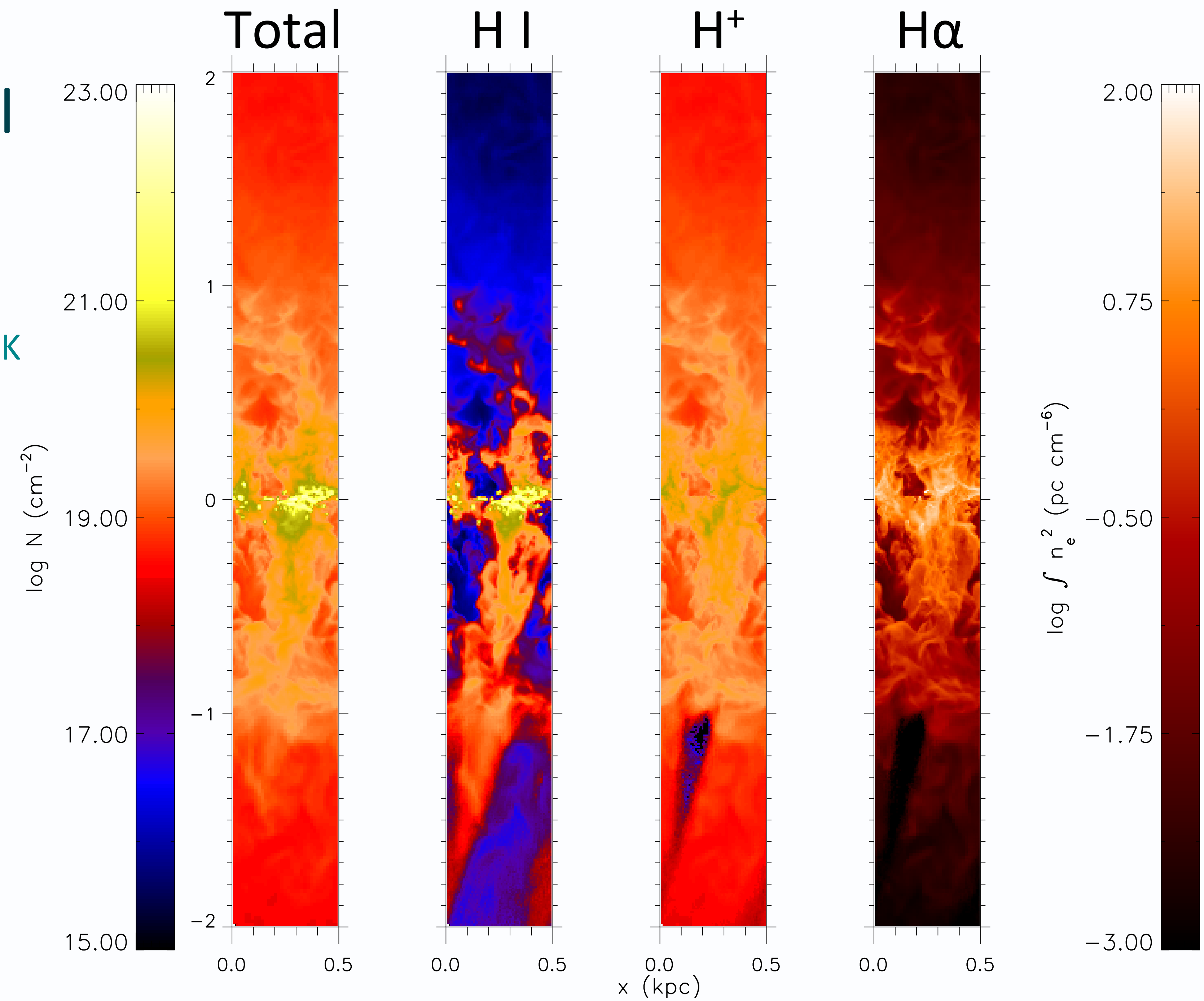
Turbulence and ionisation

Consider hydrodynamical simulations of a multi-phase, turbulent ISM

- Supernovae drive turbulence
- Heating and cooling from 10 K to > 10^8 K
- Joung & Mac Low (2006, 2009 ApJ)

Photoionise snapshot of simulations

- Use Monte Carlo photoionisation radiative transfer code
- O stars placed near the midplane
- Ionising photons can escape the midplane through low-density paths established by turbulence
- Total ionising flux is the crucial parameter
- Wood, Hill, Joung et al (2010 ApJ)



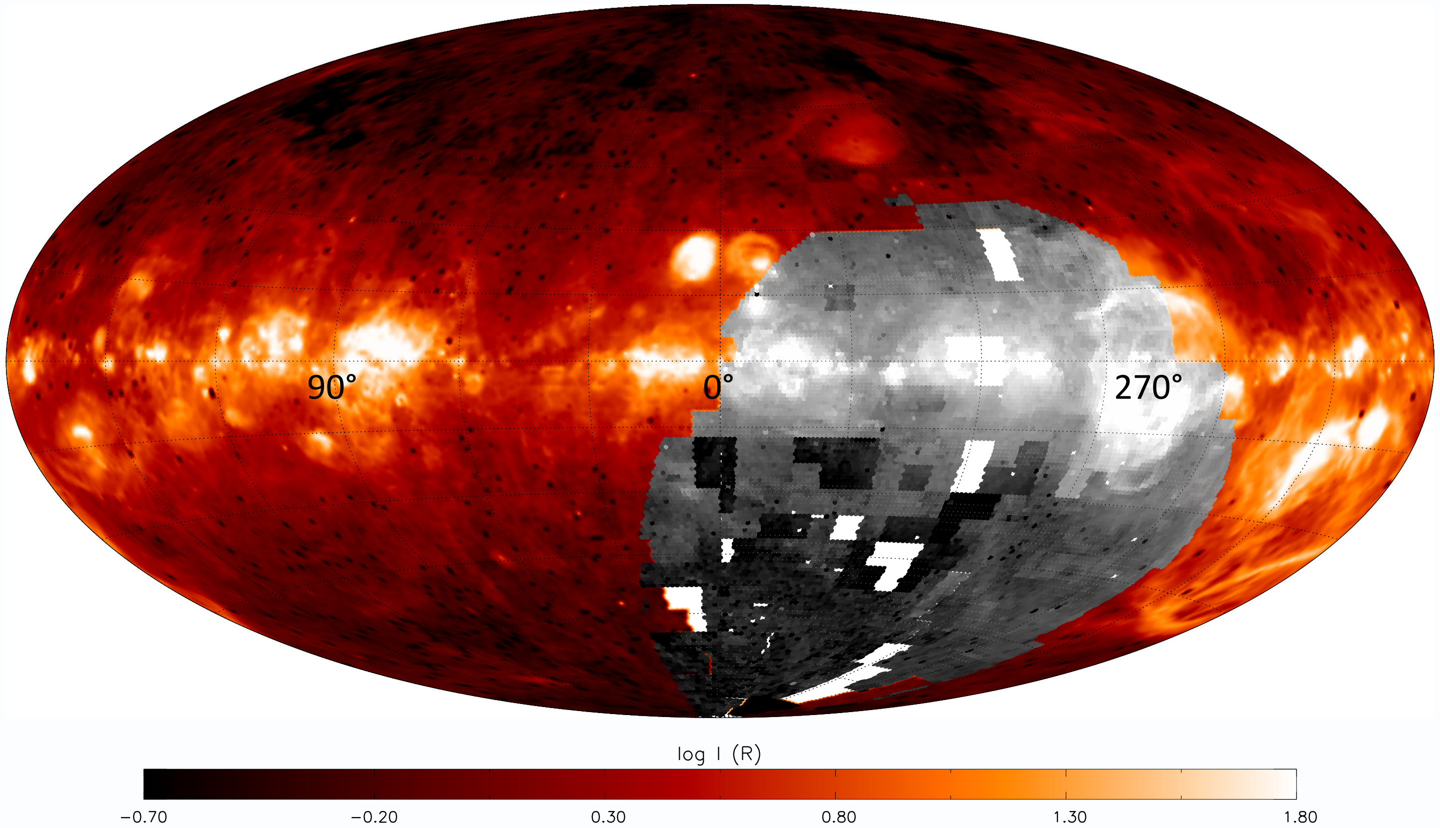
Wood, Hill, Joung et al (2010 ApJ)

Conclusions

The future

WHAM Southern Sky Survey

- WHAM moved to Cerro Tololo in Chile in 2009
- WHAM southern sky survey now underway
  - Hα observations south of δ = -30° >95% complete
  - Data reduction under way
  - Obtaining [N II] and [S II] for much of the $\delta < 0°$ Galactic plane to $|b| \approx \pm 30°$



Haffner et al (2010, ASP Conf Ser, arXiv, with recent updates)

Warm ionised medium summary

Observations

- Pulsar dispersion
  - column density $N(H^+) \approx 23$ pc cm^{-3} = 7×10^{19} cm^{-2}
    - ≈1/4 of the total hydrogen column, and 90% of H^+ mass in Milky Way ISM
  - scale height 1–1.4 kpc
- Hα
  - Detected in every direction with WHAM
  - Lower ionisation parameter (10^{-3} – 10^{-4}) than H II regions
- Forbidden line ratios
  - Low-intensity Hα is distinct from classical H II regions
  - 6000 K $\lesssim$ T $\lesssim$ 10000 K

Modelling

- Turbulence allows O stars in the plane to ionise the WIM
- The WIM is a natural consequence of feedback from massive stars in a star-forming galaxy
- Scattered light from H II regions in the plane may contribute up to ≈20% of the diffuse Hα
  (Reynolds et al 1973 ApJ; Wood & Reynolds 1999 ApJ; Witt et al 2010 ApJ)

Outstanding questions (cf Haffner et al 2009 Rev Mod Phys)

- What causes the elevated temperature (above photoionisation)?
- How much ionising radiation escapes from the Galaxy?
  - Ionisation bounded or density bounded?
- How does the WIM fit into the turbulent, multi-phase ISM?

Thank You

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$$\frac{[\mathrm{N\ II}]}{H\alpha} = 1.62 \times 10^5\, T_4^{0.4}\, e^{-2.18/T_4} \left(\frac{\mathrm{N}^+}{\mathrm{N}}\right) \left(\frac{\mathrm{N}}{\mathrm{H}}\right) \left(\frac{\mathrm{H}^+}{\mathrm{H}}\right)^{-1}$$

$$\frac{[\mathrm{S\ II}]}{[\mathrm{N\ II}]} = 4.62\, e^{0.04/T_4} \left(\frac{\mathrm{S}^+}{\mathrm{S}}\right) \left(\frac{\mathrm{S}}{\mathrm{H}}\right) \left[\left(\frac{\mathrm{N}^+}{\mathrm{N}}\right) \left(\frac{\mathrm{N}}{\mathrm{H}}\right)\right]^{-1}$$

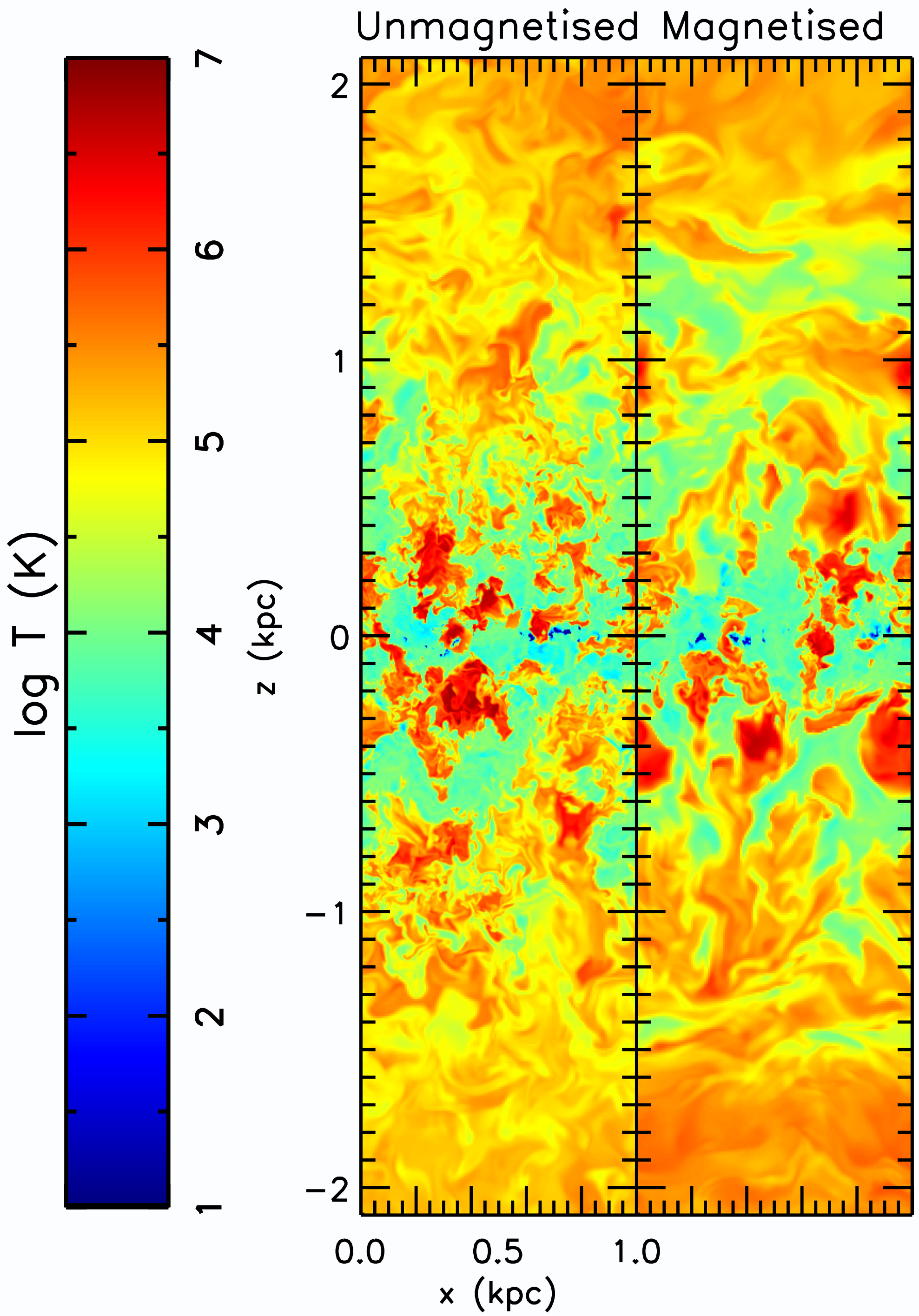
$$\frac{[\mathrm{N\ II}]\lambda 5755}{[\mathrm{N\ II}]\lambda 6584} = 0.192\, e^{-2.5/T_4}$$

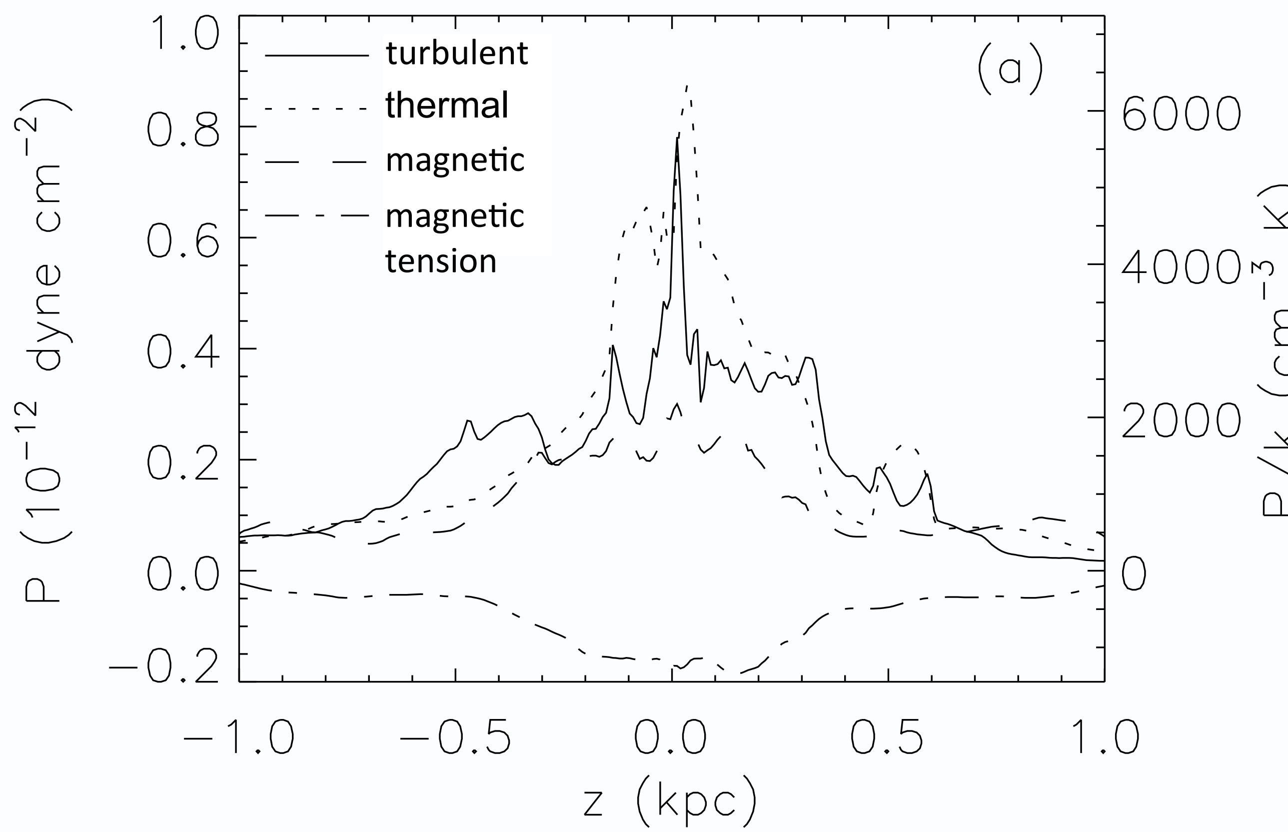
$$\frac{[\mathrm{O\ III}]}{H\alpha} = 1.74 \times 10^5\, T_4^{0.4}\, e^{-2.88/T_4} \left(\frac{\mathrm{O}^{++}}{\mathrm{O}}\right) \left(\frac{\mathrm{O}}{\mathrm{H}}\right) \left(\frac{\mathrm{H}^+}{\mathrm{H}}\right)^{-1}$$

$$\frac{\mathrm{He\ I}}{H\alpha} = 0.47\, T_4^{-0.14} \left(\frac{\mathrm{He}^+}{\mathrm{He}}\right) \left(\frac{\mathrm{He}}{\mathrm{H}}\right) \left(\frac{\mathrm{H}^+}{\mathrm{H}}\right)^{-1}$$

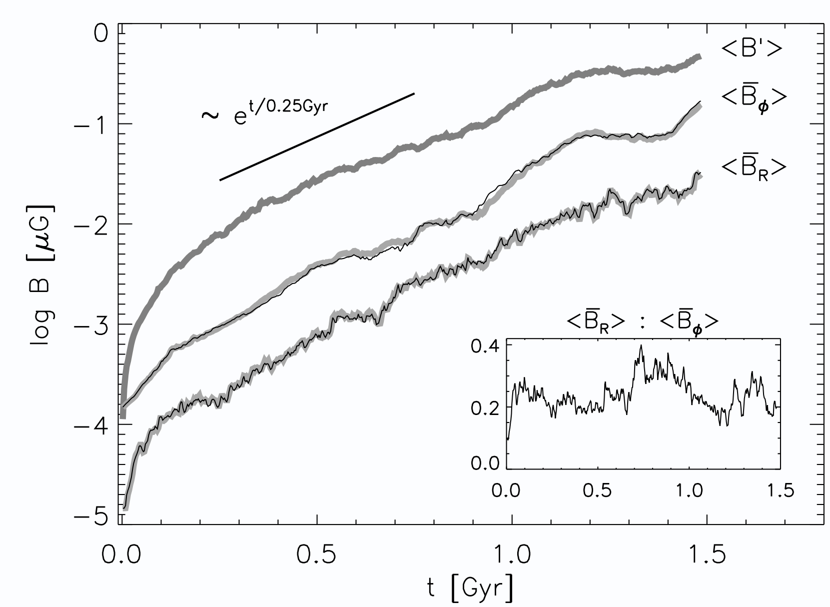
Haffner et al (1999 ApJ); Madsen, Reynolds, & Haffner (2006 ApJ)

Vertical support



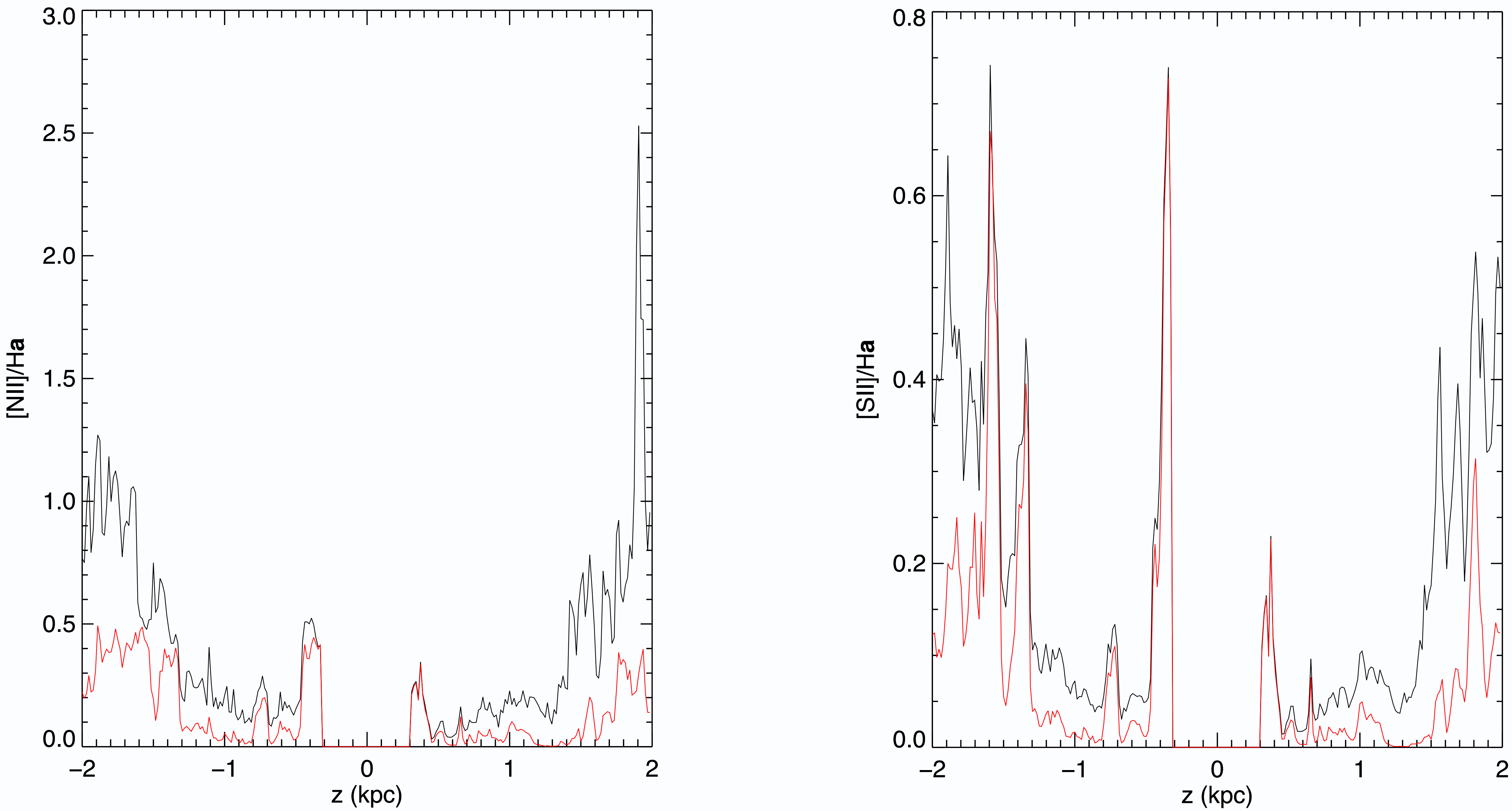


Hill et al (2012 ApJ)



Gressel et al (2008 A&A, AN)

Multi-temperature photoionisation modelling



J Barnes & K Wood (in prep)