The Warm Ionized Medium

S. R. Kulkarni

RADIOPHYSICS

Spectrum of the Galactic Radio Emission between 10 Mc/s and 1·5 Mc/s

As part of a general investigation of cosmic radio noise at frequencies less than 10 Mc/s the intensity of the radiation has been measured at 9·8 Mc/s, 4·8 Mc/s, 2·3 Mc/s and 1·5 Mc/s. The observations were made at Hobart during July and August in 1961 and 1962. Similar arrays of three full-wave dipoles were used at each frequency, directed to declination −42°. The bandwidth of the receivers was 4 kc/s and a combination of frequency sweeping and minimum recording was used to reduce interference from transmitting stations and atmospherics. The receivers were calibrated with noise generators.

Fig. 1 shows samples of the records at 4·8 Mc/s, 2·3 Mc/s and 1·5 Mc/s. Only records for which ionospheric modulation of the radiation appeared to be absent were used in calculating the intensities. The ionospheric critical penetration frequency, foF_2, was on a number of occasions less than 1 Mc/s and many records were obtained which reproduced the galactic sidereal profile.

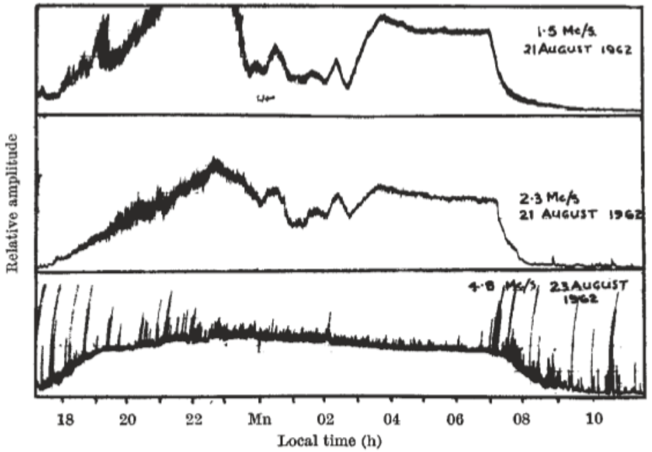

Fig. 1. Sample records of cosmic radio noise at 1·5 Mc/s, 2·3 Mc/s and 4·8 Mc/s. The first two records illustrate the effects of transmitter interference from 1900 to 2400 h and ionospheric modulation from 2400 h to 0300 h. The galactic profile appears from 0400 h to 0700 h

Fig. 2 shows the spectra of the maximum and minimum galactic intensities, observed near 1900 R.A. and 0400 R.A., respectively. The spectrum of the maximum at frequencies less than 10 Mc/s should be interpreted with caution since high-resolution studies at 4·8 Mc/s (to be reported elsewhere) have shown much fine detail near the plane of the Milky Way. This spectrum represents an average over bright and dark regions. The spectrum of the minimum, on the other hand, is not affected significantly by spatial averaging.

Also shown in Fig. 2 are the corresponding spectra obtained in 1956[1]. It may be seen that the present spectra agree well between 2 Mc/s and 10 Mc/s. However, it now appears that the intensity decreases more below 2 Mc/s than was previously thought. In particular the 900 kc/s intensity was obtained in 1956 under rather unusual ionospheric conditions and may have to be revised in a downward direction when further results become available. It should be noted that the spectral maximum occurs at a higher frequency near the plane of the galaxy than at high galactic latitudes. In addition, at frequencies less than the spectral maximum, the intensity varies very nearly as the square of the frequency. Both of these effects may be explained in terms of absorption of the radiation in interstellar ionized gas. Their theoretical implications are discussed elsewhere[3].

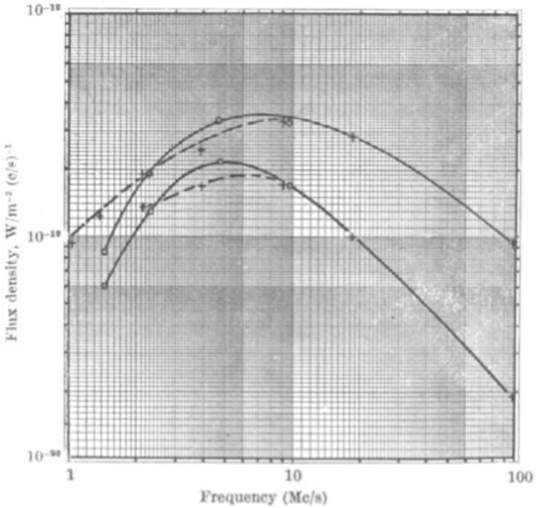

Fig. 2. Cosmic noise spectra less than 100 Mc/s. The 1956 spectra are shown dotted. Points above 10 Mc/s from ref. 2. Present observations indicated thus ○

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G. R. A. Ellis
M. D. Waterworth
M. Bessell

Department of Physics,
University of Tasmania,
Hobart.

[1] Ellis, G. R. A., *J. Geophys. Res.*, **62**, 229 (1957).
[2] Higgins, C. S., and Shain, C. A., *Austral. J. Phys.*, **7**, 460 (1954).
[3] Hoyle, F., and Ellis, G. R. A., *Austral. J. Phys.* (in the press).

ON THE EXISTENCE OF AN IONIZED LAYER ABOUT THE GALACTIC PLANE

By F. Hoyle* and G. R. A. Ellis†

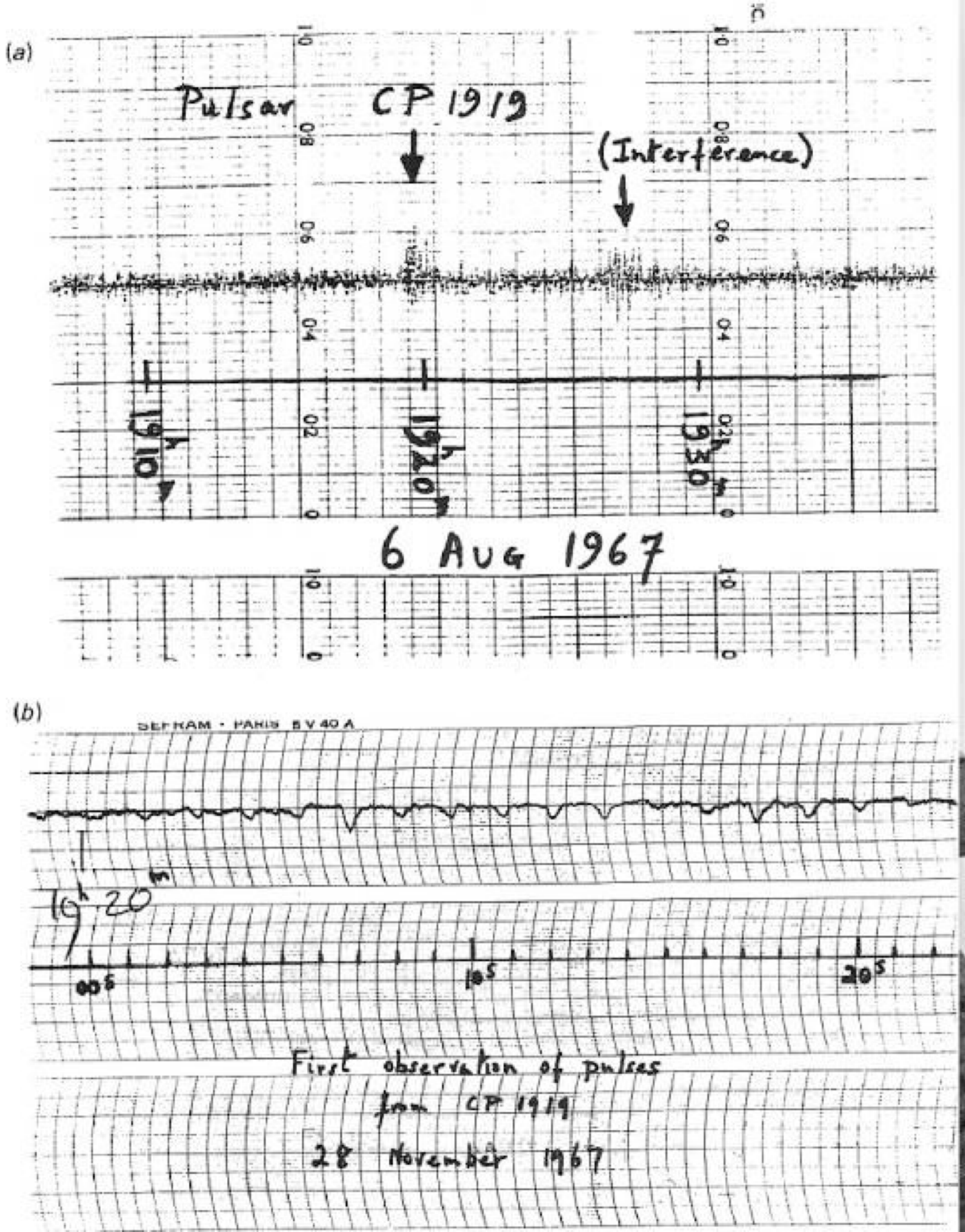
[*Manuscript received November* 8, 1962]

Summary

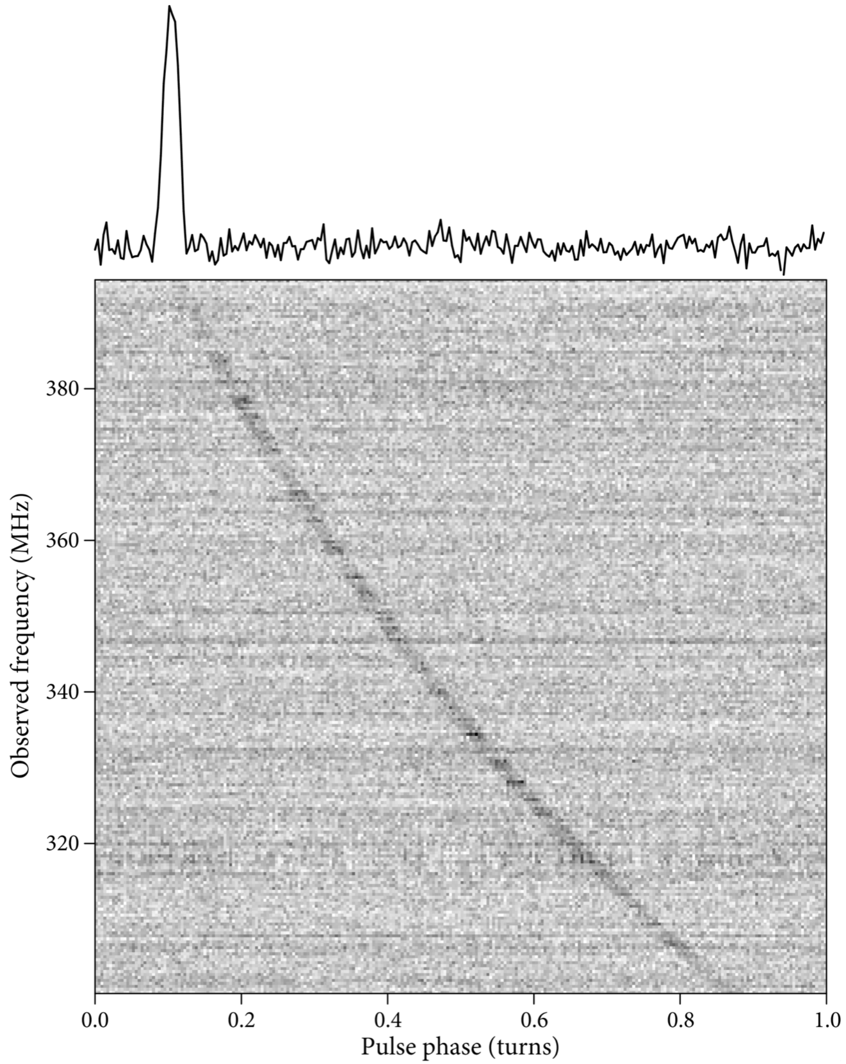
The radio frequency spectrum observed in directions towards the galactic pole shows a maximum near 5 Mc/s. It seems unlikely that the synchrotron process responsible for the emission can give such a maximum and it is suggested that the observed fall in the flux density at lower frequencies is caused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

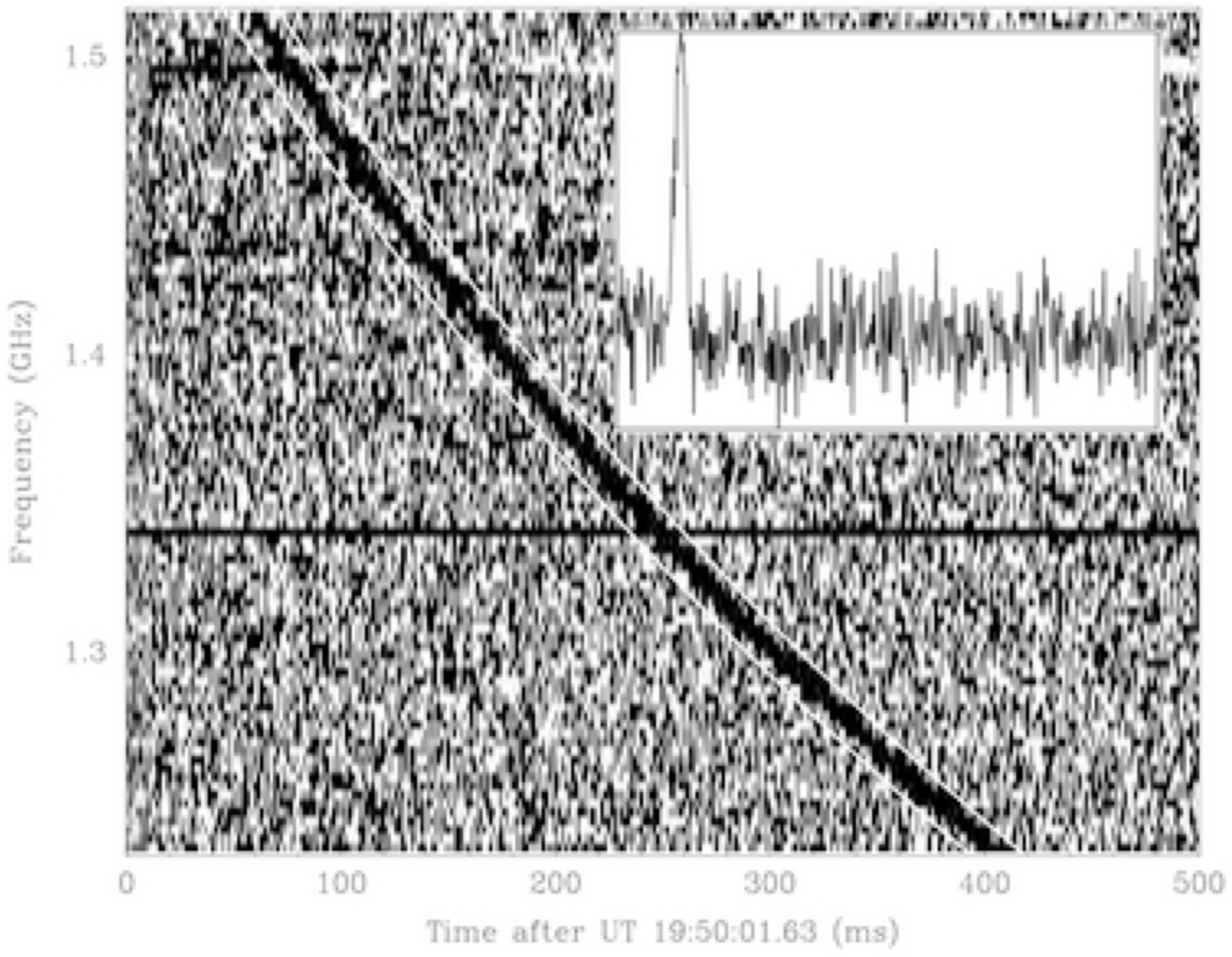
The electron density is found to be about $0 \cdot 1$ cm^{-3} so that along a line of sight to the galactic pole there are of the order of 10^{20} electrons. The mass of the layer is $\sim 5\times10^8 M_\odot$ and its rate of radiation in the Balmer continuum is $10^7 L_\odot$. The radiation rate per unit volume is $\sim 10^{-26}$ erg cm^{-3} s^{-1} in the Balmer continuum and the total radiation rate is $\sim 5\times10^{-26}$ erg cm^{-3} s^{-1}, a value close to the average emission of ionizing radiation by O and B stars.


(a)
Pulsar CP 1919
(Interference)
19h10m
19h20m
19h30m
6 AUG 1967
(b)
19h20m
00s
10s
20s
First observation of pulses
from CP 1919
28 November 1967

All pulsars showed “dispersion”



Pulsar Dispersion Sweep



Discovery of FRB
Lorimer et al. 2007

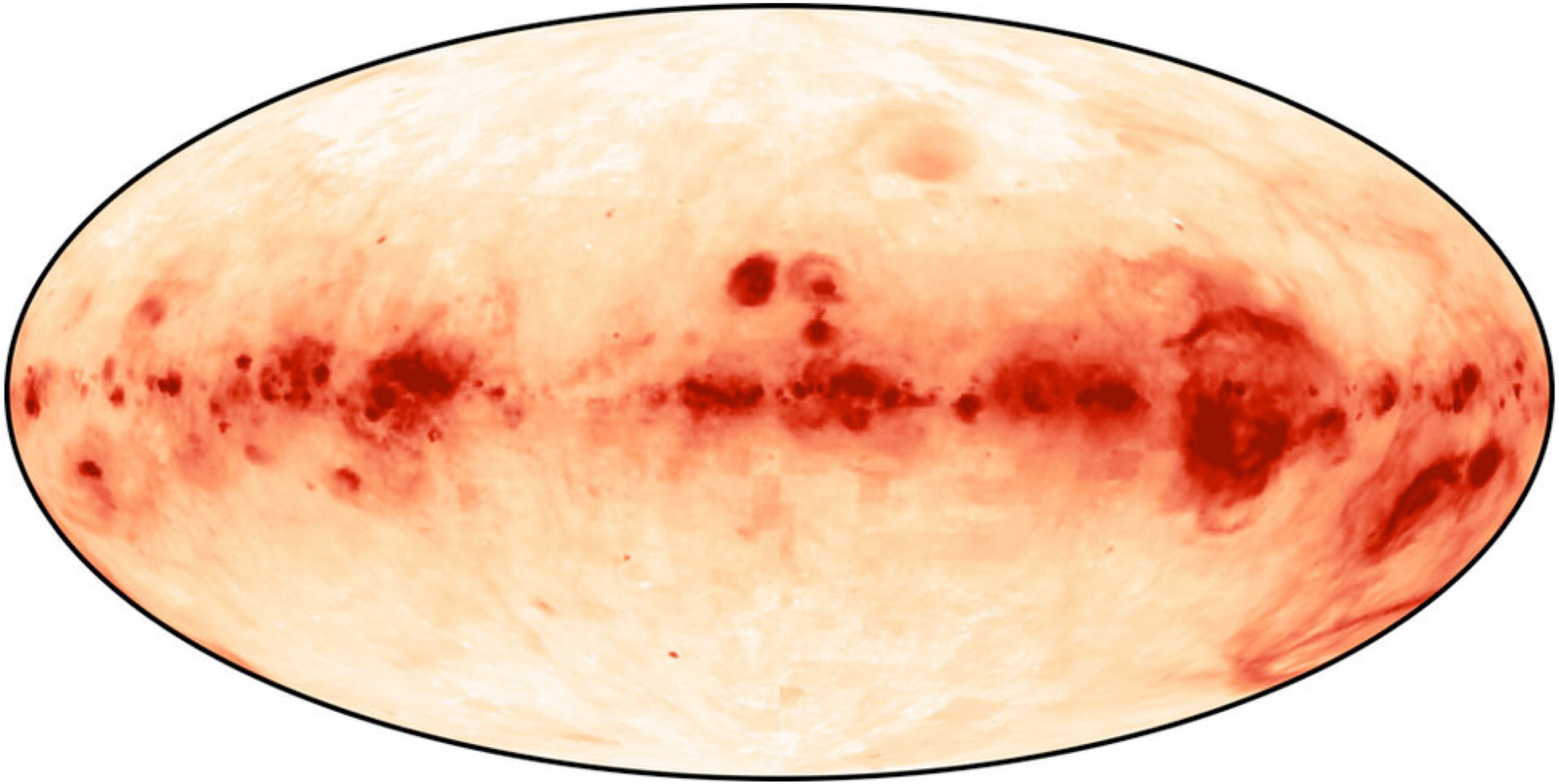
Enter the optical astronomers

Fabry-Perot imaging in H-alpha & nebular lines

Wisconsin H-alpha Mapper (WHAM)

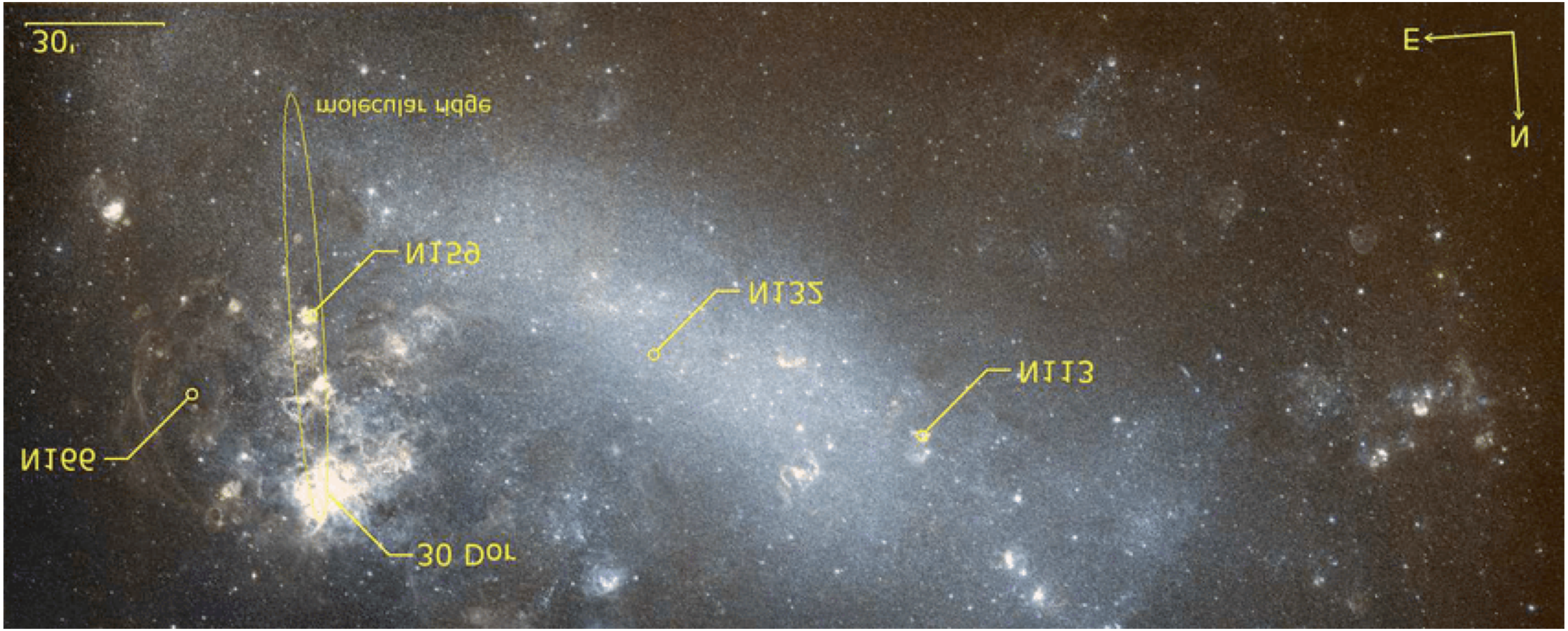
- Fabry-Perot Imager
- Beam: 1 degree diameter
- 1-sigma: 0.1 Rayleigh
- Work horses: Hα, [NII], [SII]
- Other optical lines:
  - [OI], [NI], [OII], [OIII]
  - [NeIII], [SIII], [ArIII]

The Galaxy in H-alpha (WHAM)

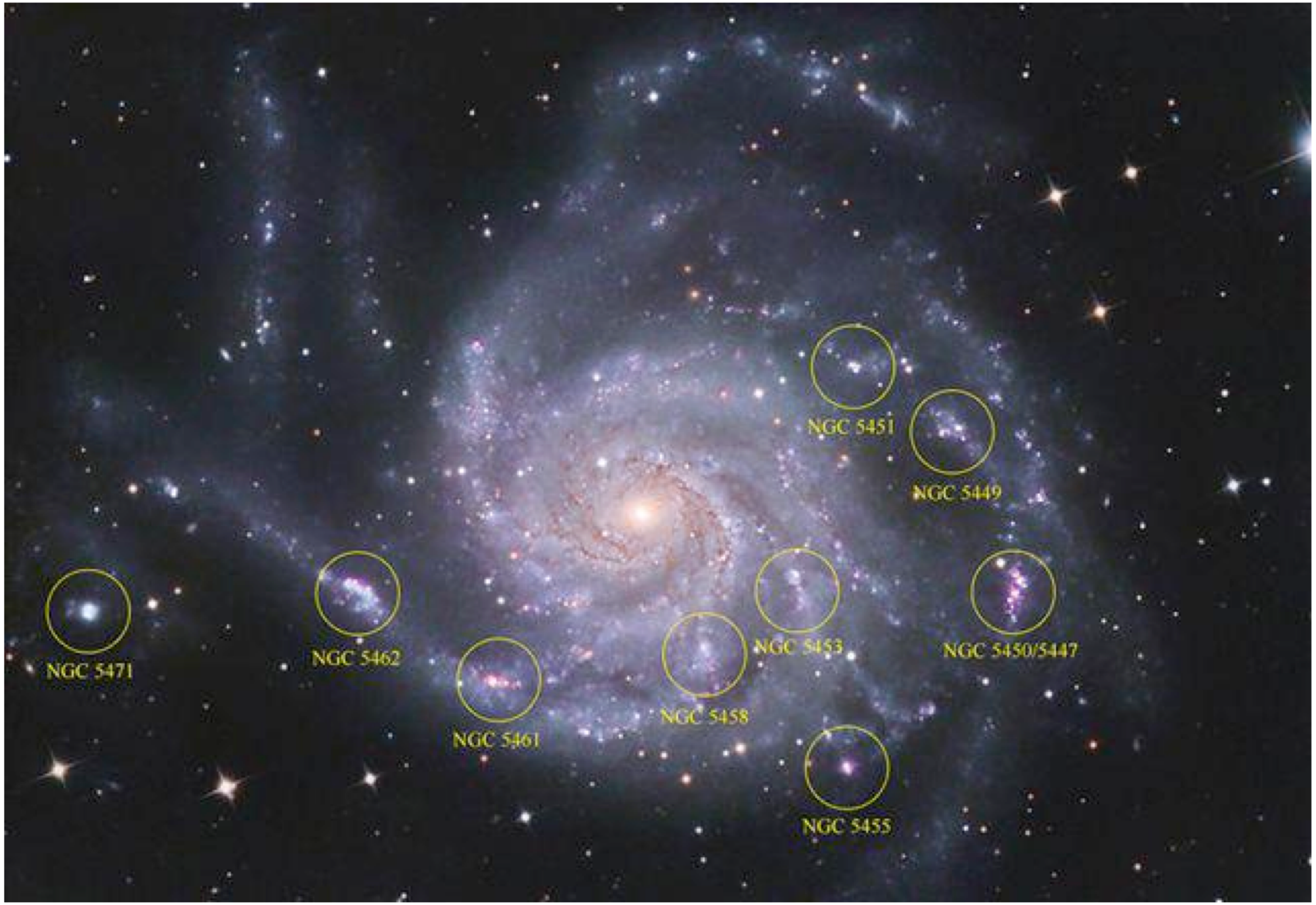


Our nearest dwarf galaxies

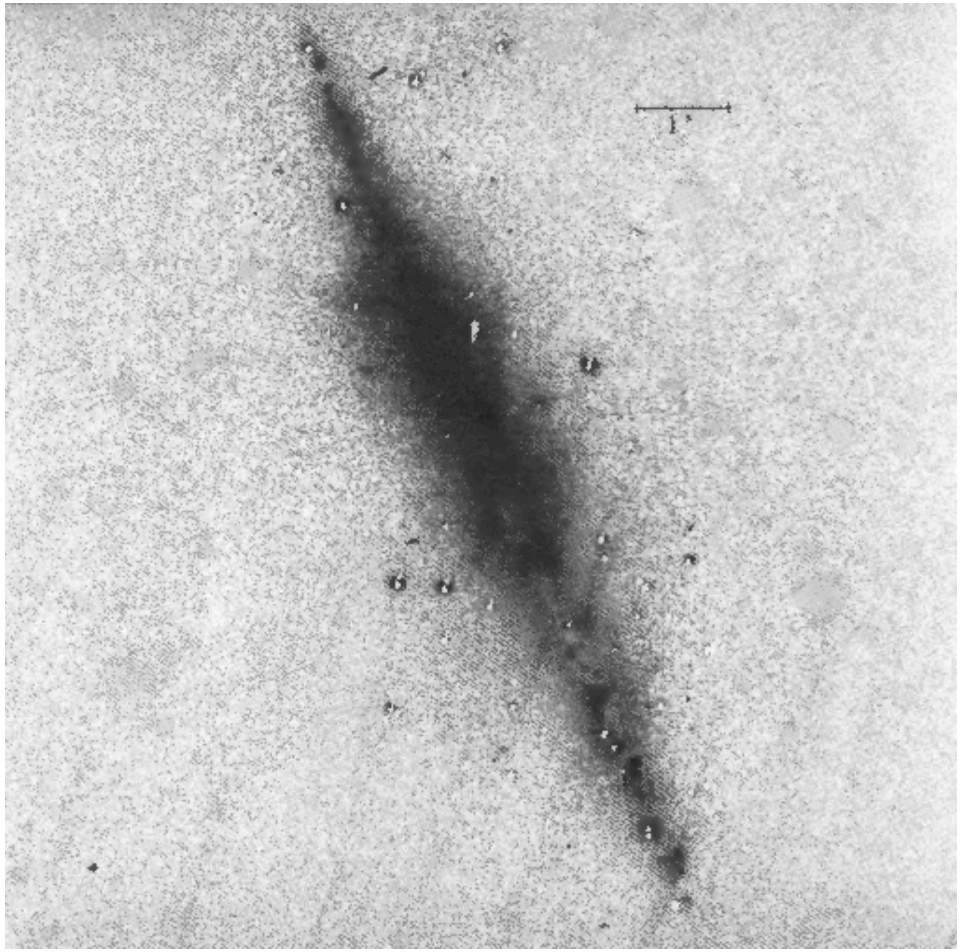
HII regions and Diffuse Ionized gas in LMC

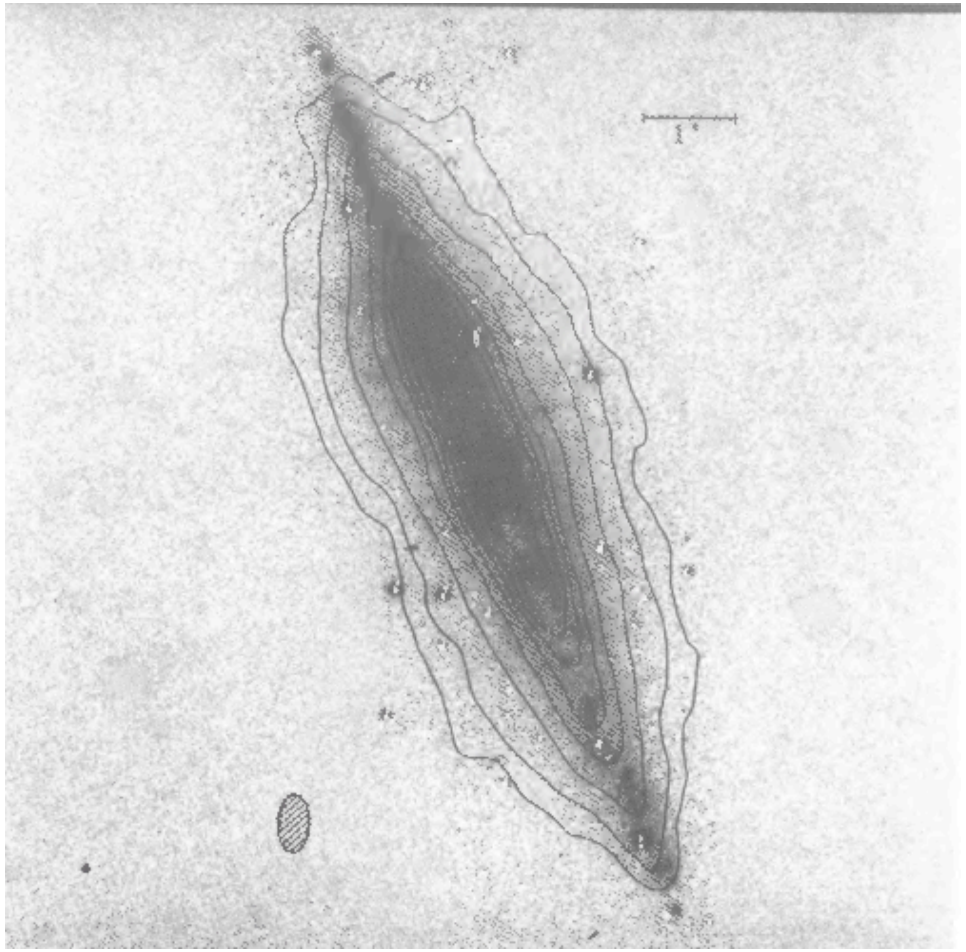


Messier 101


NGC 5451
NGC 5449
NGC 5471
NGC 5462
NGC 5453
NGC 5450/5447
NGC 5461
NGC 5458
NGC 5455

WIM in other galaxies





Richard Rand (PhD thesis, Caltech)

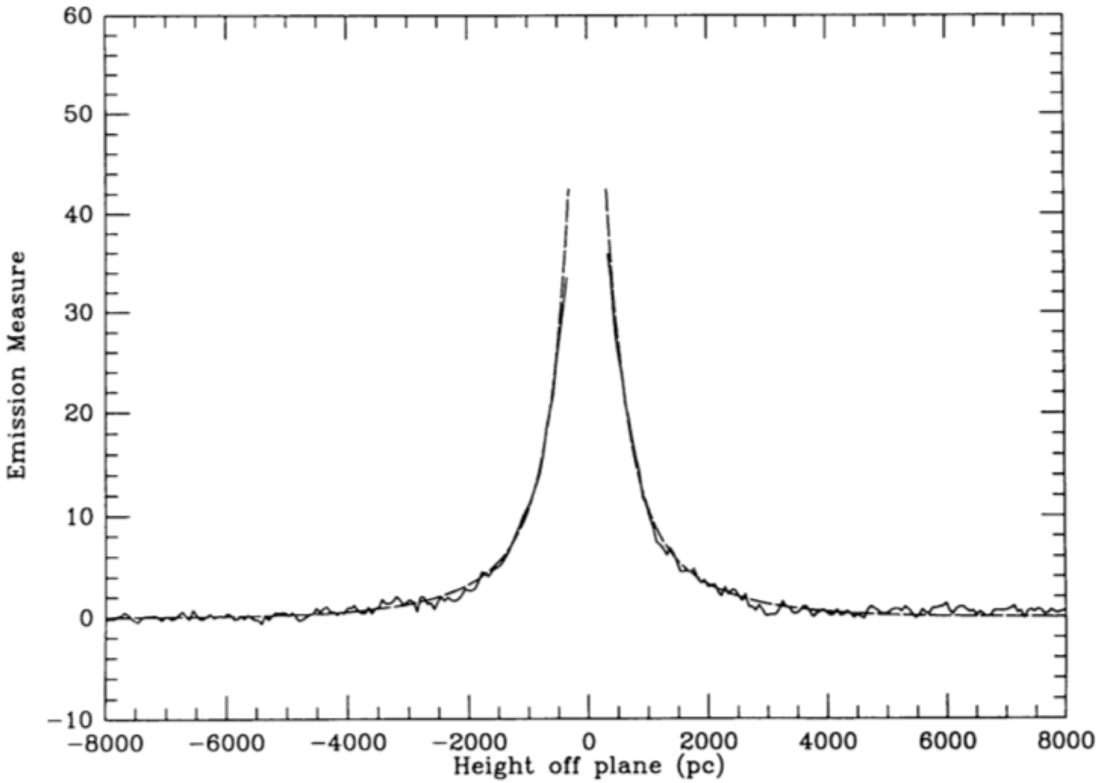


FIG. 2*a*

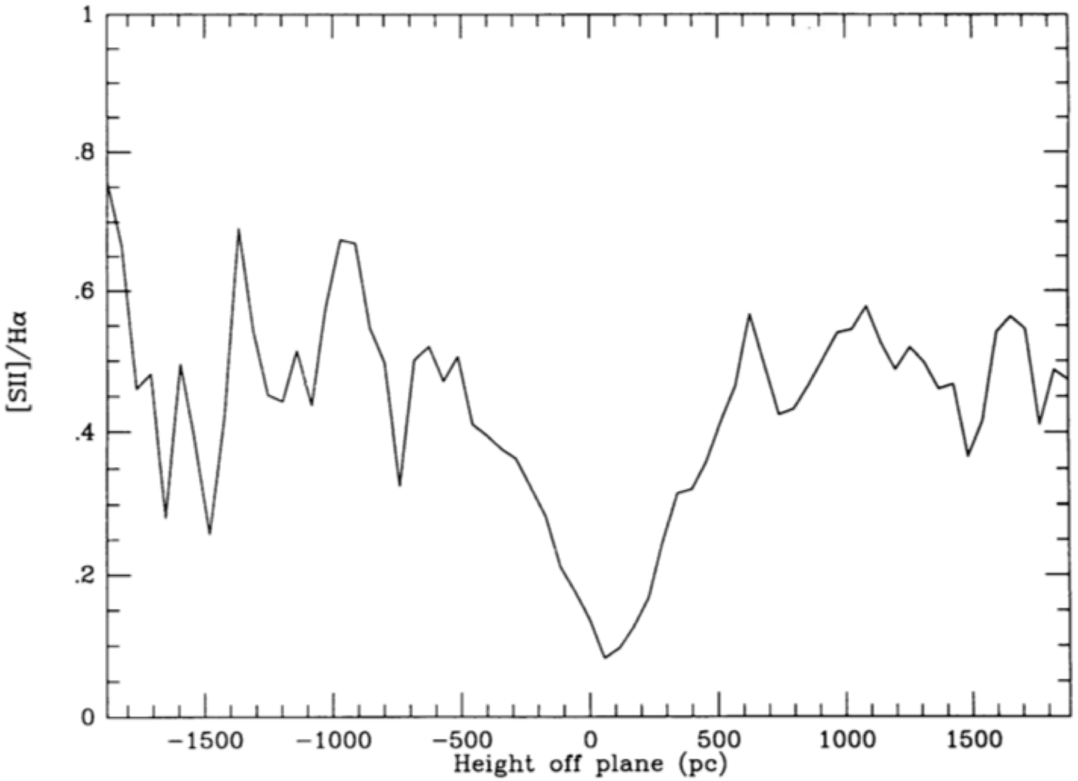
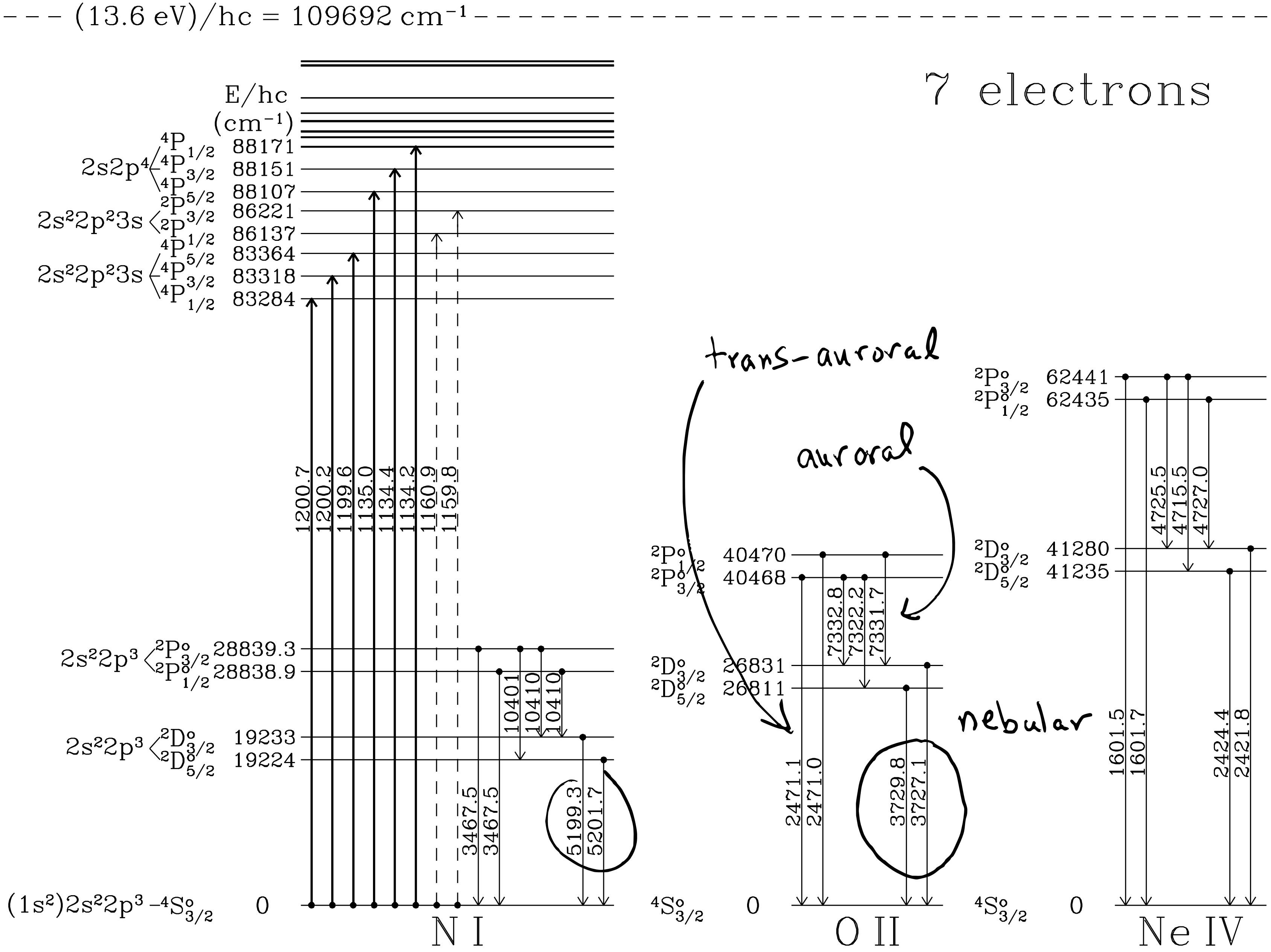


FIG. 2*b*

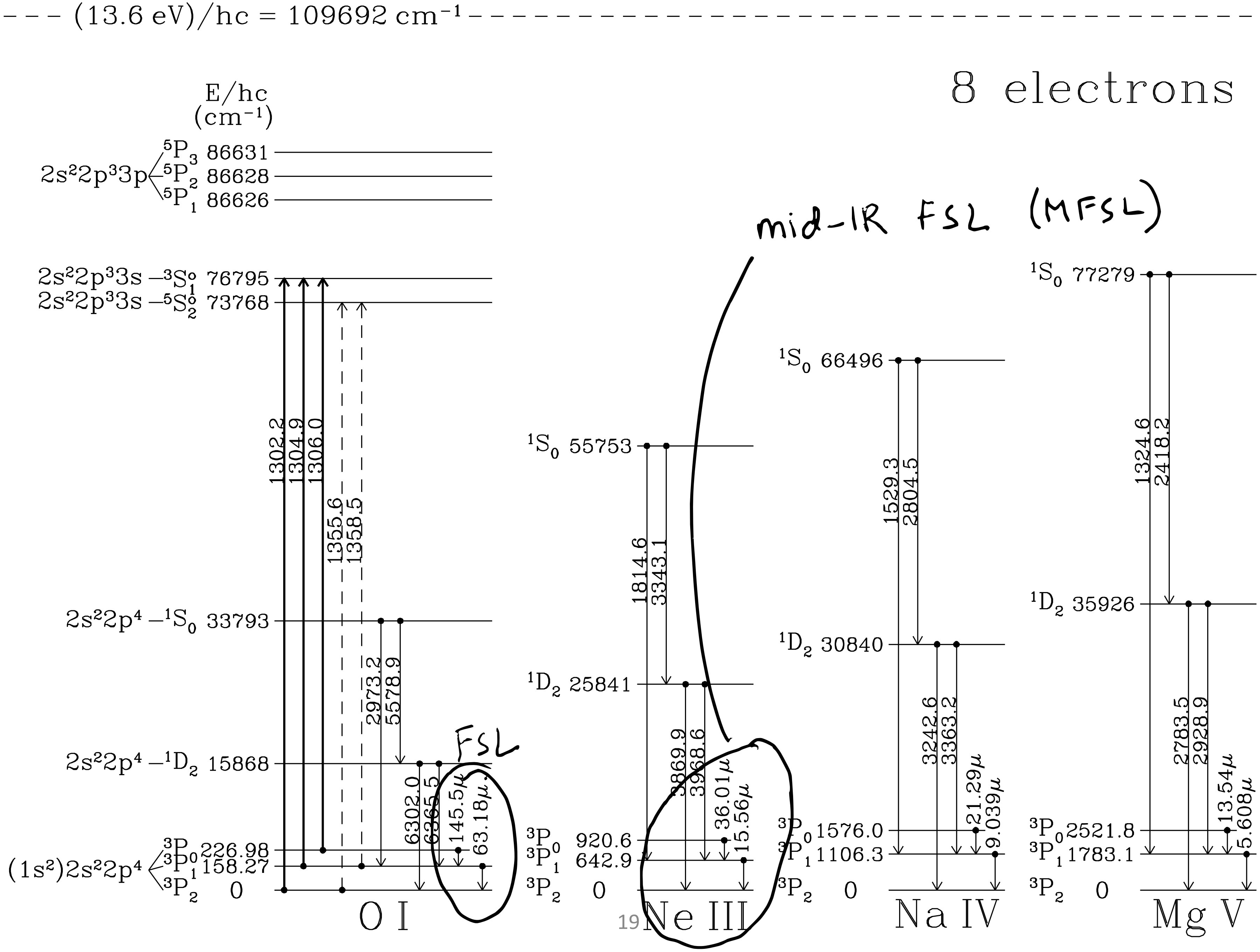
FIG. 2.—(*a*) The vertical distribution of emission measure averaged over the range 2–5 kpc north of the nucleus, for $z > 300$ pc, and our fit to the distribution (*dashed* line). (*b*) The vertical distribution of the [S II]/Hα ratio through a bright H II region in the plane at about 500 pc SW of the nucleus. Absolute calibration of the [S II] data has *not* been done. The value of the ratio at the midplane has been arbitrarily set to 0.1, the typical value for Galactic H II regions.

Probing via “nebular” lines

7 electrons


(13.6 eV)/hc = 109692 cm⁻¹
E/hc
(cm⁻¹)
2s2p⁴ ⁴P1/2 88171
⁴P3/2 88151
⁴P5/2 88107
2s²2p²3s ²P3/2 86221
²P1/2 86137
2s²2p²3s ⁴P5/2 83364
⁴P3/2 83318
⁴P1/2 83284
1200.7
1200.2
1199.6
1135.0
1134.4
1134.2
1160.9
1159.8
2s²2p³ ²P°3/2 28839.3
²P°1/2 28838.9
2s²2p³ ²D°3/2 19233
²D°5/2 19224
10401
10410
10410
3467.5
3467.5
5199.3
5201.7
(1s²)2s²2p³ ⁴S°3/2 0
N I
trans-auroral
auroral
nebular
²P°1/2 40470
²P°3/2 40468
7332.8
7322.2
7331.7
²D°3/2 26831
²D°5/2 26811
2471.1
2471.0
3729.8
3727.1
⁴S°3/2 0
O II
²P°3/2 62441
²P°1/2 62435
4725.5
4715.5
4727.0
²D°3/2 41280
²D°5/2 41235
1601.5
1601.7
2424.4
2421.8
⁴S°3/2 0
Ne IV

8 electrons



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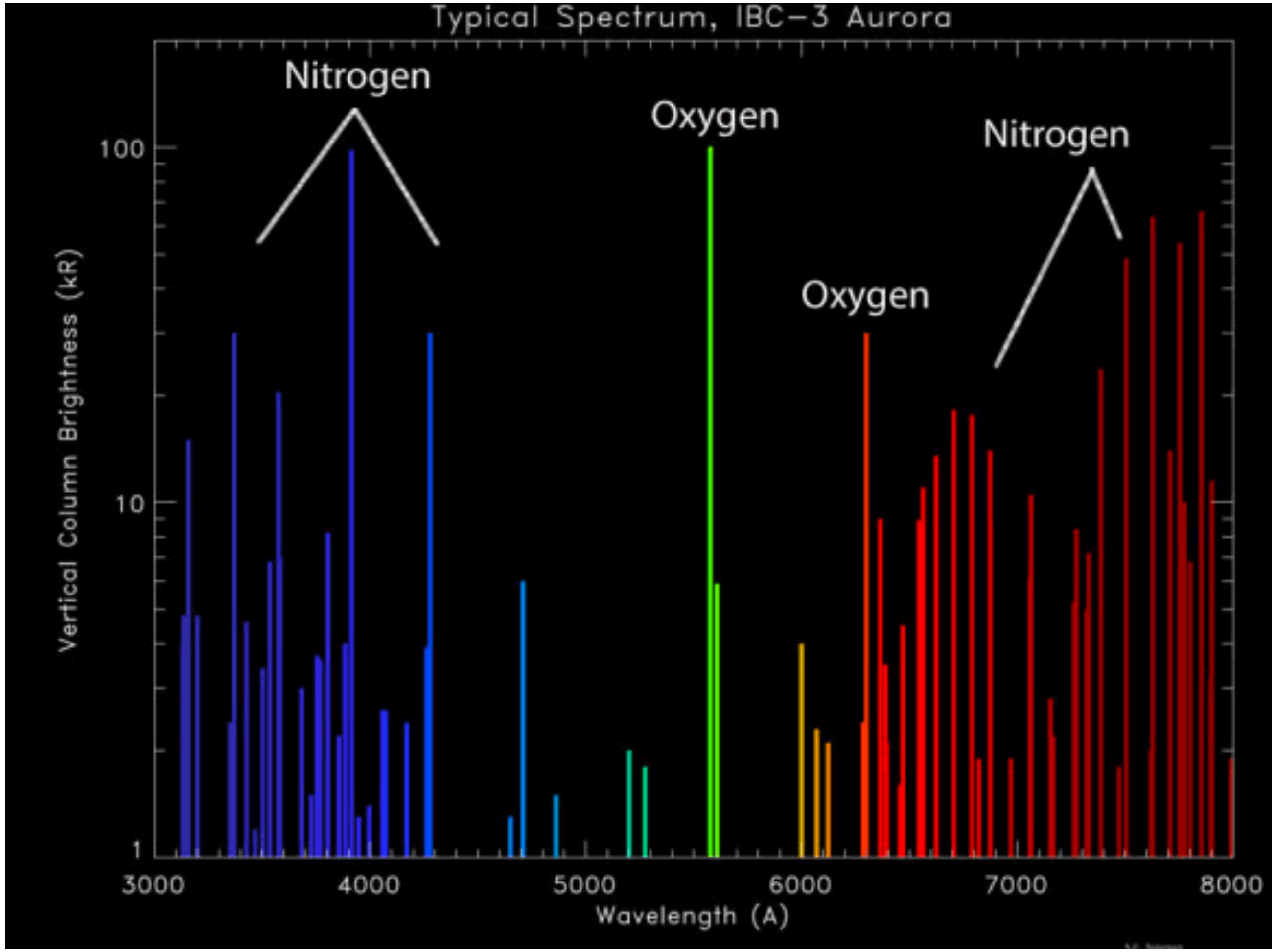
An aside: Night sky

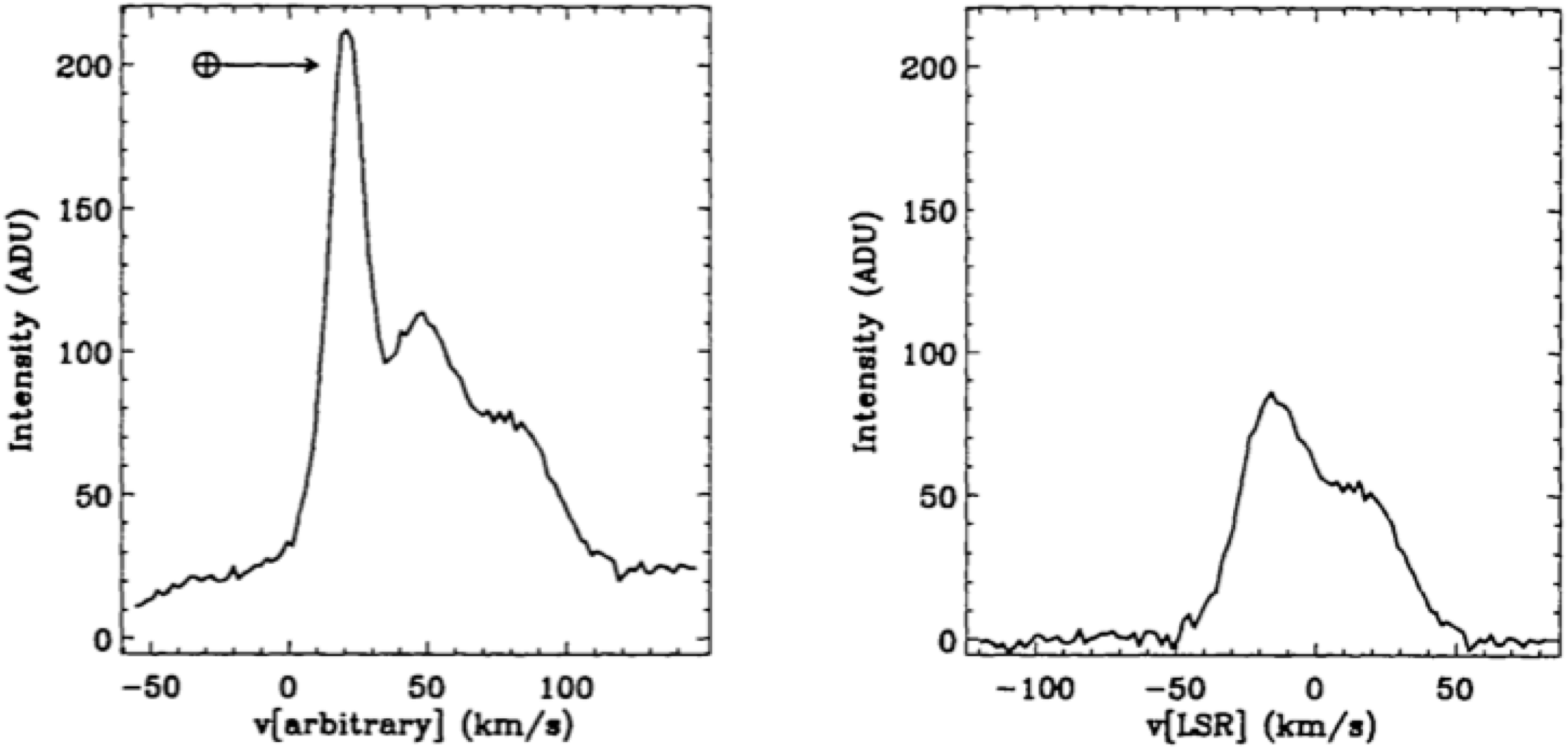
The spectrum of the Aurora



WIM lines are faint, compete with auroral emission

WHAM Halpha data (Left): Includes geocoronal Halpha emission (marked with symbol for Earth. (Right): geocoronal emission removed

Reynolds, R. J. ASP Conf # 168, p149 (1999)



Rayleigh: Unit for intensity. Defined to be 10^6 phot/cm^2/second/steradian

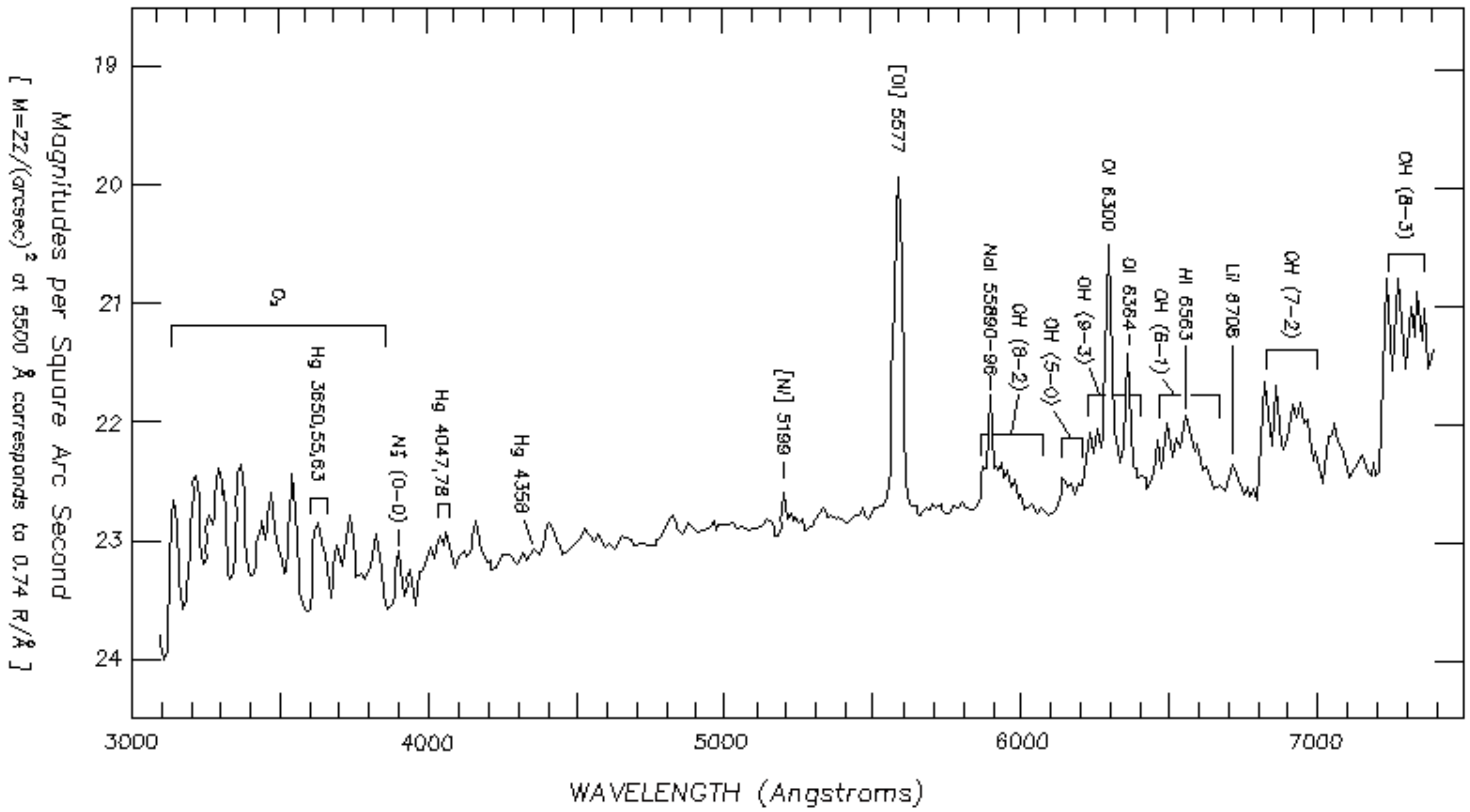
Mauna Kea night sky

Night sky brightness in U increases by a factor of 5 at quarter moon and 65 at full moon. Corresponding values in V are 1.3 at quarter and 5 at full moon. These rough estimates are of are, of course, for clear (cirrus-free) nights.

Average sky brightness at zenith during dark time is given in the table below.

Color	Equivalent (lambda, um)	Brightness [mag/(")^2]	Flux [phot./cm^2/s/ microns/(")^2]
U	0.36	21.6	1.74x10e-2
B	0.44	22.3	1.76x10e-2
V	0.55	21.1	3.62x10e-2
R	0.64	20.3	5.50x10e-2
I	0.79	19.2	1.02x10e-1
J	1.23	14.8	2.49
H	1.66	13.4	4.20
K	2.22	12.6	3.98

http://www.cfht.hawaii.edu/Instruments/ObservatoryManual/CFHT_ObservatoryManual_%28Sec_2%29.html

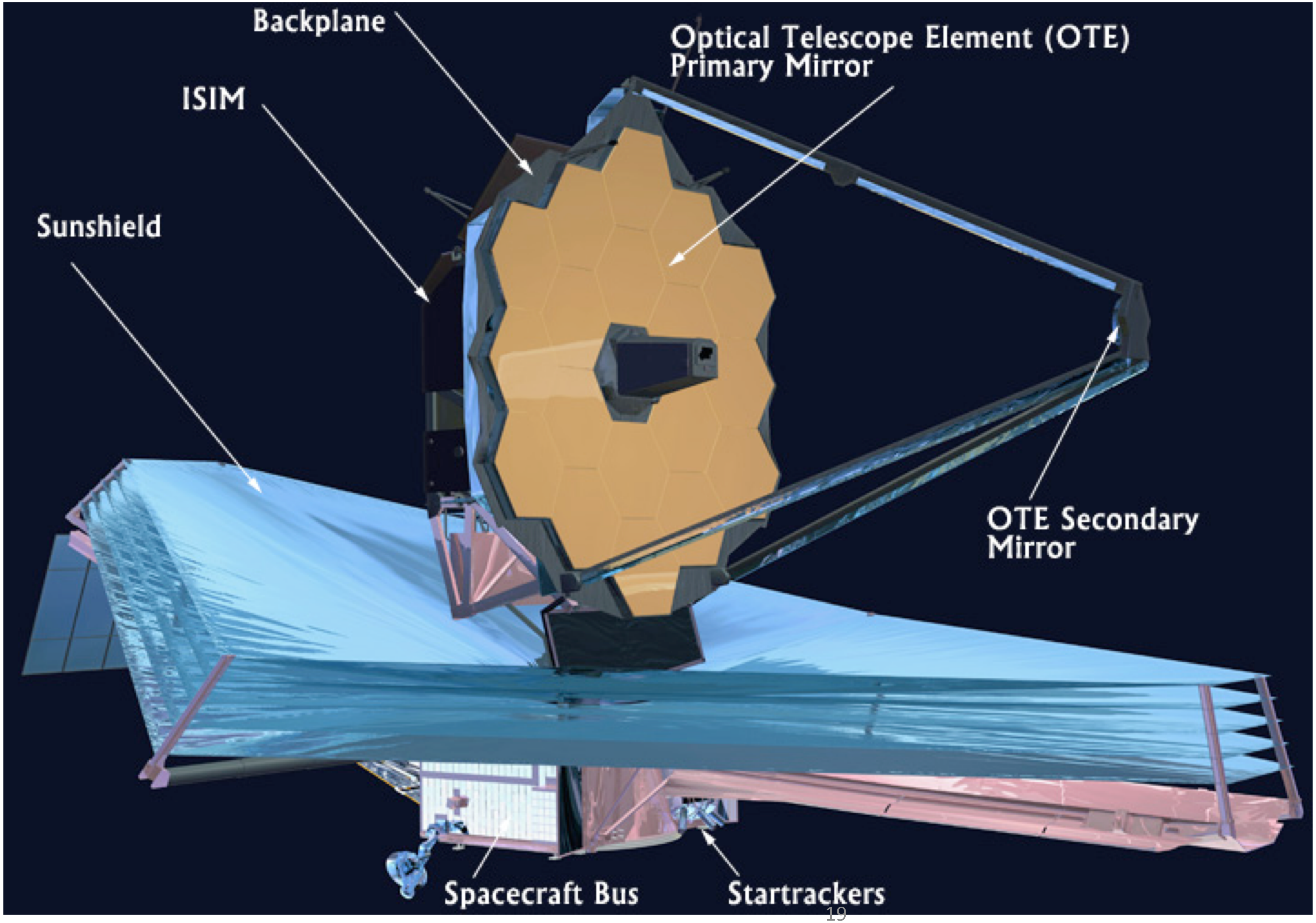


Magnitudes per Square Arc Second
[M=22/(arcsec)² at 5500 Å corresponds to 0.74 R/Å]
WAVELENGTH (Angstroms)
19
20
21
22
23
24
3000
4000
5000
6000
7000
O₂
Hg 3650,55,63
N₂⁺ (0–0)
Hg 4047,78
Hg 4358
[NI] 5199
[OI] 5577
NaI 5890–96
OH (8–2)
OH (5–0)
OH (9–3)
OI 6300
OI 6364
OH (6–1)
HI 6563
LiI 6708
OH (7–2)
OH (8–3)

Probing Diffuse Ionized Gas

- Free-free absorption & emission (low frequency)
- Pulsar dispersion measure
- Rotation measure of polarized sources (including Galactic synch)
- Recombination radiation (primarily H-alpha)
- Collisionally excited lines [NII], [SII], weak lines of [OI], [NI], [OIII]
- Radio Recombination Lines (Rydberg atoms)
- 2 Photon continuum (near UV)
- resonance lines in absorption (UV)
- *Mid-IR fine structure lines*

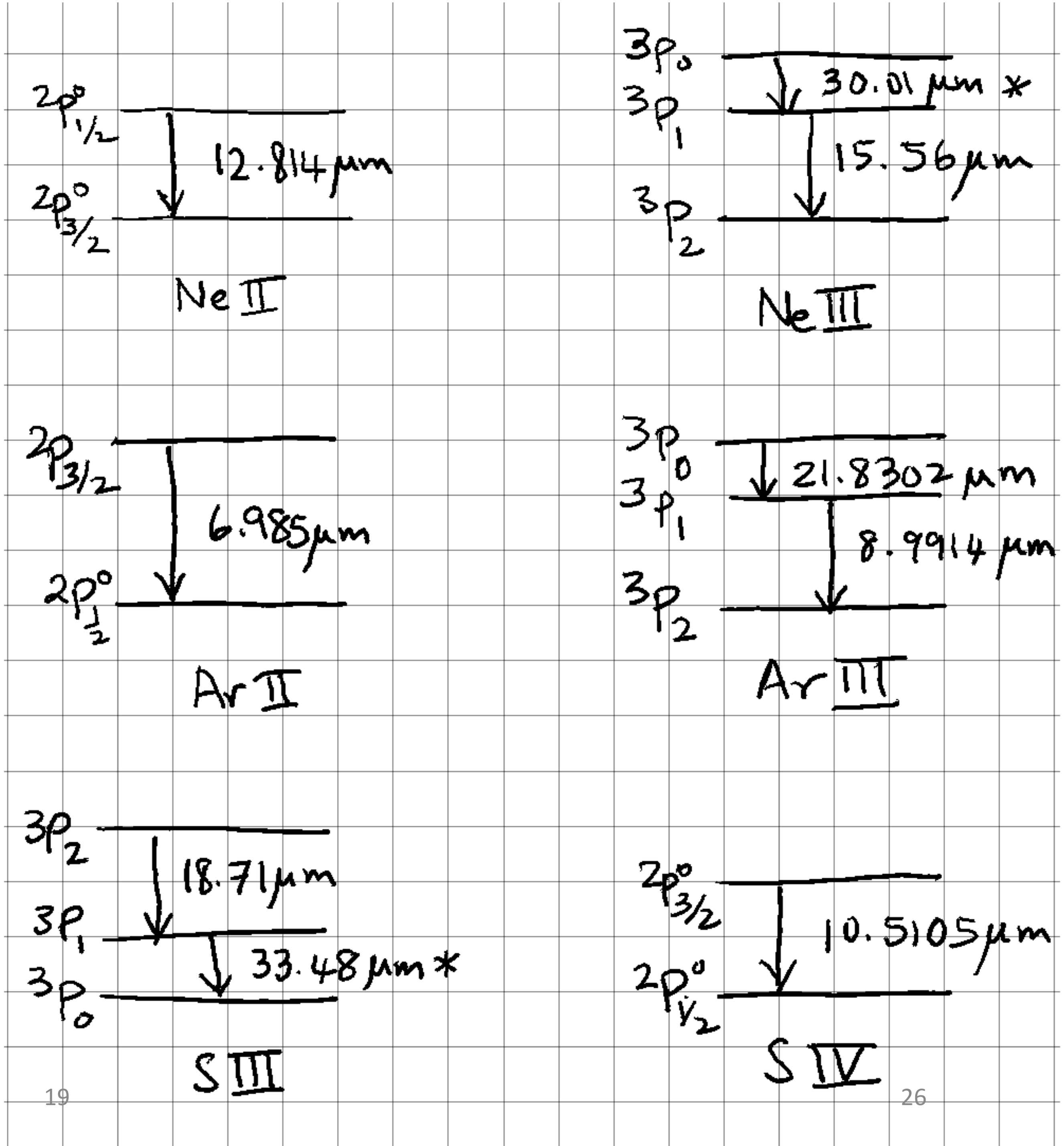
A renaissance in WIM studies: JWST & ground-based IFU program



Collecting area:
25.4 m^2

Table 1. Ionization Potential

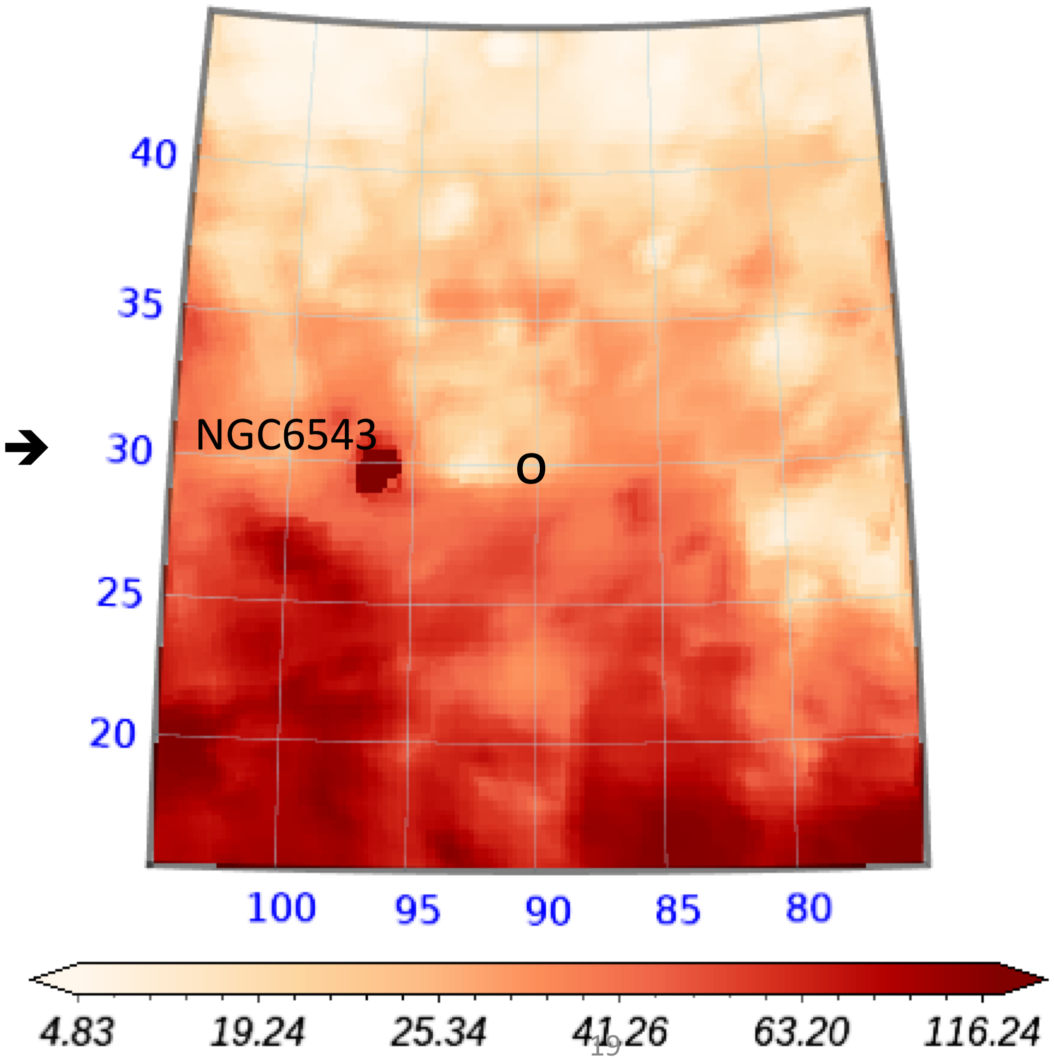
X	Y_X (ppm)	I→II	II→III	III→IV
Ne	93.3	21.6	41.0	63.4
S	14.5	10.4	23.3	34.8
Ar	2.75	15.8	27.6	40.7
N	74.1	14.5	29.6	47.4



Wisconsin H-alpha Mapper (WHAM)

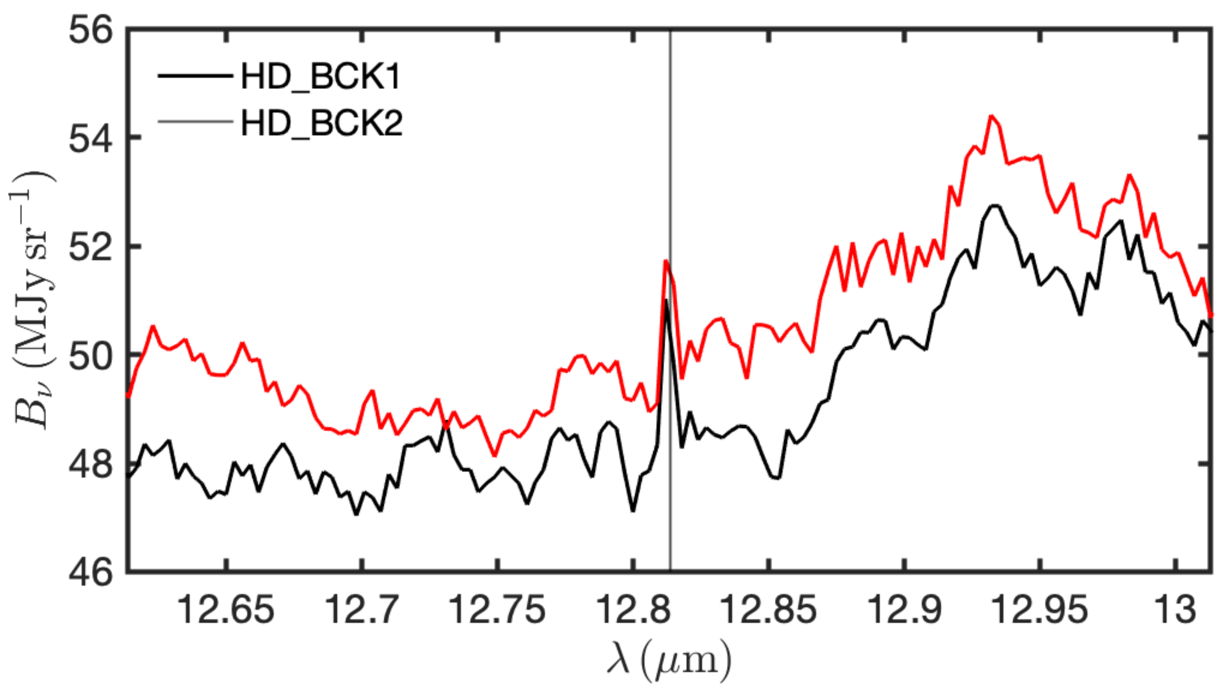
WHAM beam is 1-degree across!

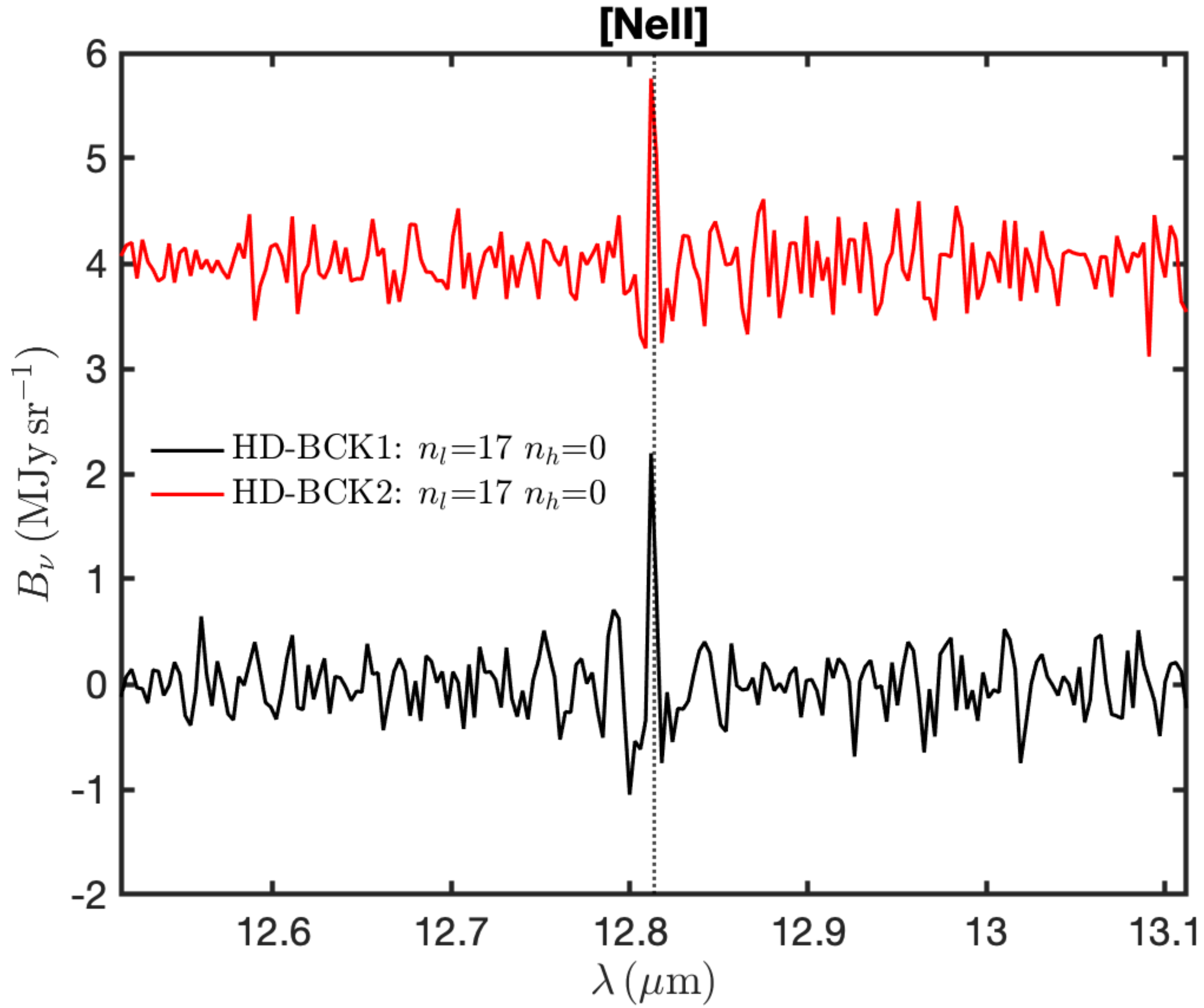
Galactic latitude in degrees ➔



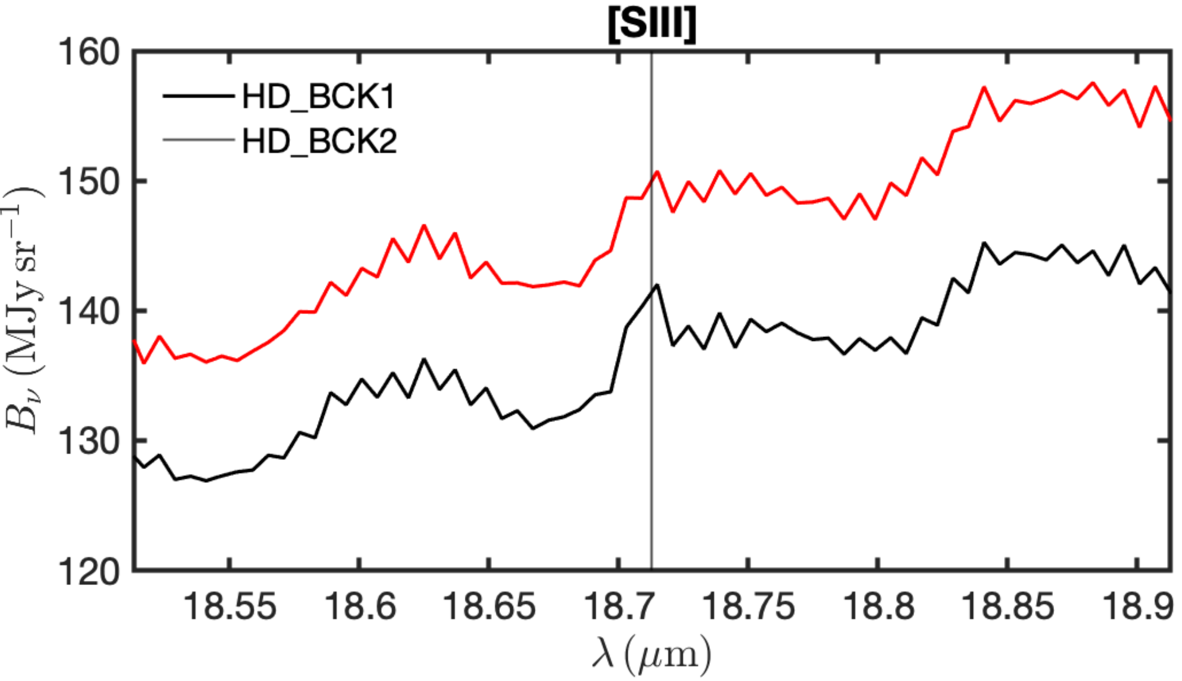
🡐 in emission measure units

[NeII]

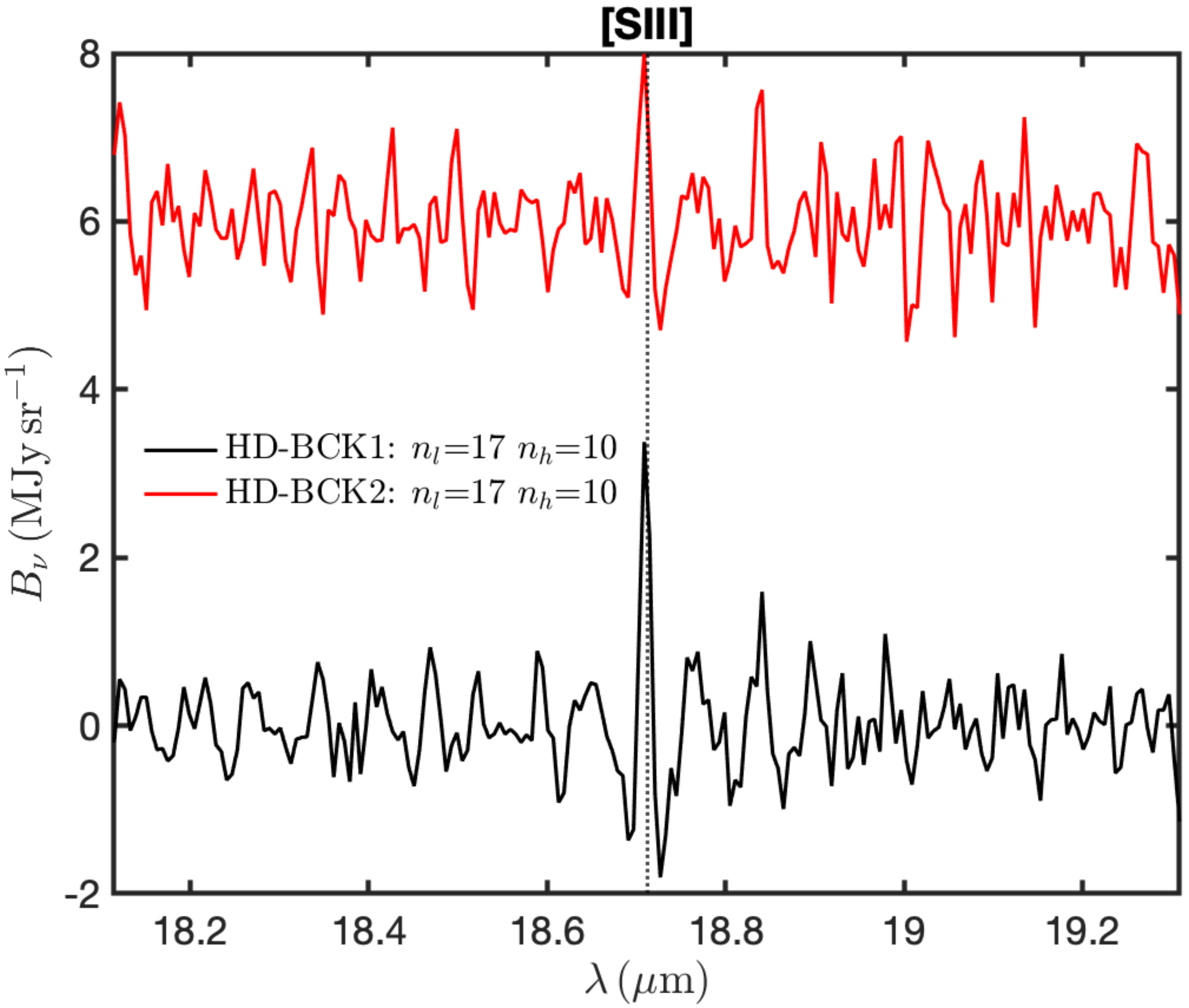

HD_BCK1
HD_BCK2
56
54
52
50
48
46
12.65
12.7
12.75
12.8
12.85
12.9
12.95
13
$B_\nu\,(\mathrm{MJy\,sr^{-1}})$
$\lambda\,(\mu\mathrm{m})$


[NeII]
HD-BCK1: n_l=17 n_h=0
HD-BCK2: n_l=17 n_h=0
6
5
4
3
2
1
0
-1
-2
12.6
12.7
12.8
12.9
13
13.1
$B_\nu\,(\mathrm{MJy\,sr^{-1}})$
$\lambda\,(\mu\mathrm{m})$

[SIII]


[SIII]
HD_BCK1
HD_BCK2
160
150
140
130
120
18.55
18.6
18.65
18.7
18.75
18.8
18.85
18.9
B_ν (MJy sr^{-1})
λ (μm)

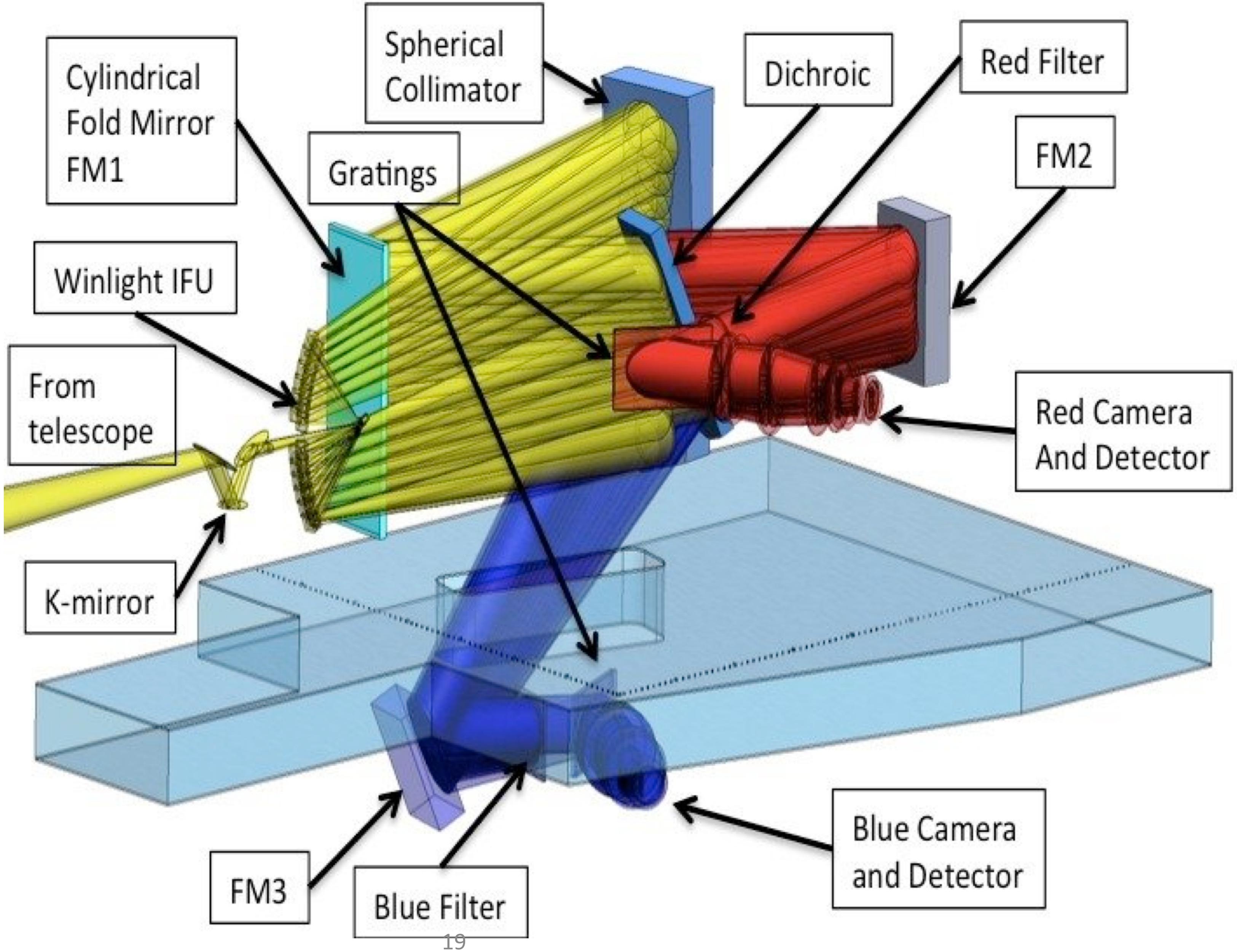
19


[SIII]
HD-BCK1: n_l=17 n_h=10
HD-BCK2: n_l=17 n_h=10
8
6
4
2
0
-2
18.2
18.4
18.6
18.8
19
19.2
B_ν (MJy sr^{-1})
λ (μm)

Keck Cosmic Imager

PI: D. C. Martin
Morrisey et al. (2018)

FoV=20 x 8 $arcsec^2$



Projects

- Any hour-long observation of MIRI-MRS is “grist for the WIM mill”
  - “commensal” observations
- Combine this with Keck/KCI observations of the same field
  - nebular lines yield EM and T
  - a long-lived cottage industry
- **NEW:** study of WIM on arcsecond scales
  - WIM studies to date have been on tens of arcminutes scale
  - tiny nebulae have not been studied (e.g., faint ionized nebulae of A stars in the CNM or white dwarfs in the WNM)
    - filling factor of WNM!

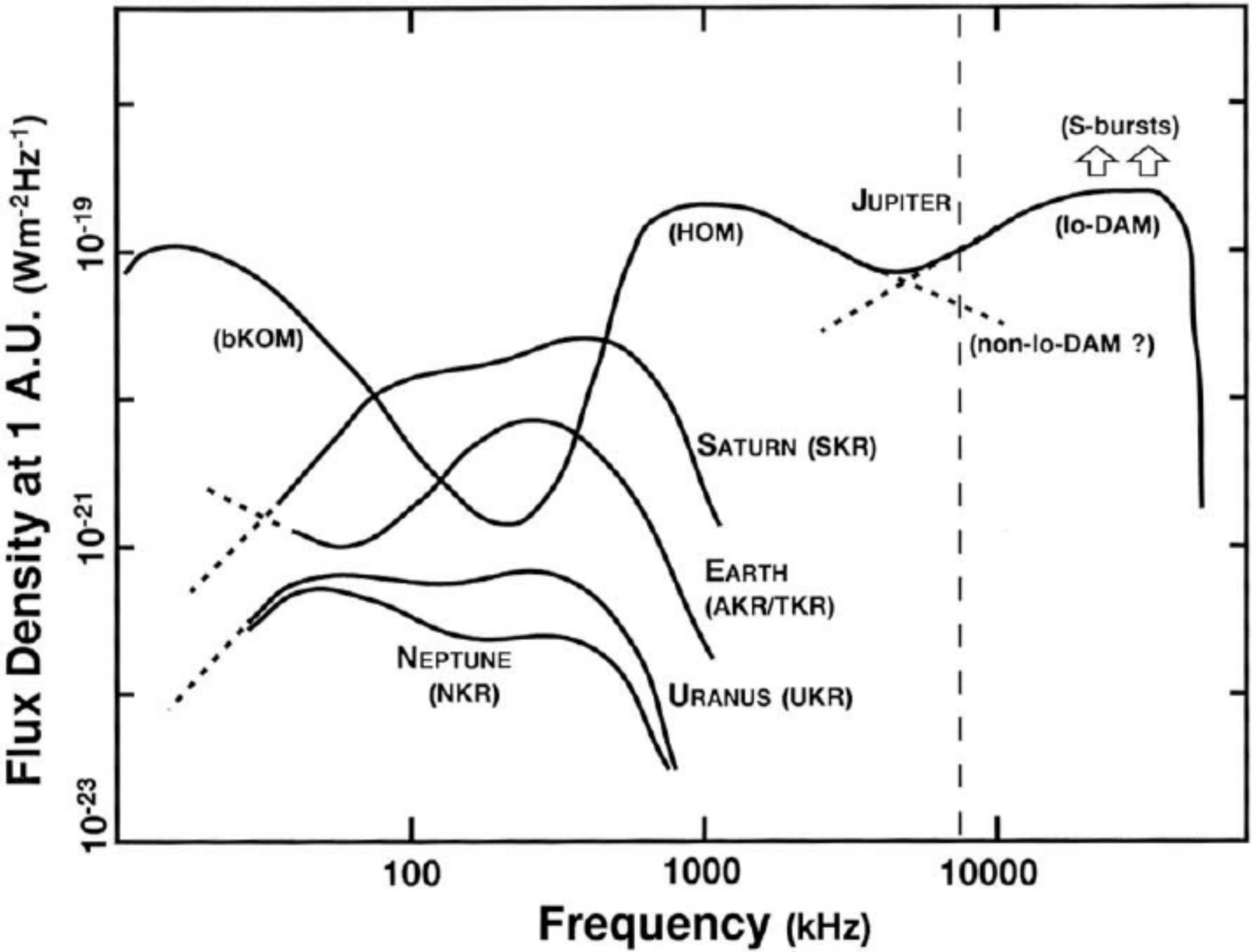
Warm Ionized Medium: Summary

The Warm Ionized Medium (WIM)

- WIM hosts 90% of the ionized gas in the Milky Way
  - HII regions are bright but total up to 10% of the ionized gas
- WIM is pervasive
  - filling factor of 0.25 in the Galactic disk & lower halo
- WIM is responsible for
  - dispersion of pulsar signals and Faraday rotation
  - free absorption & emission
  - diffuse Hα emission all over the sky
- WIM is turbulent
  - revealed via interstellar scattering & scintillation

Low Frequency Radio Astronomy

The Very Low Frequency Sky



LOFAR (Netherlands)

MWA, Australia

Long Wavelength Array (LWA), California