Optical recombination lines (9.4.2) $\alpha_\nu \ll 1$

Balmer lines observed in optical

Only need know # of particles in n_j to use eq 9.8
(expression for j_ν)

$$\Rightarrow \ldots \Rightarrow \int j_\nu d\nu = \frac{1}{4\pi} h\nu_{ji} \alpha_{ji} n_e n_i \simeq \frac{1}{4\pi} h\nu_{ji} \alpha_{ji} n_e^2$$

α: effective recombination coeff, see table 9.4

ν: freq of line center

n_e: e⁻ & ion densities, set to equal

use 6.12 with 9.13

$$\Rightarrow \ldots \Rightarrow \int_\nu I_\nu d\nu = \frac{1}{4\pi} h\nu_{ji} \alpha_{ji} n_e^2 l = 2.46 \times 10^{17} h\nu_{ji} \alpha_{ji} EM$$

$\int_\nu I_\nu d\nu$: intensity over the line

α density

α temp

EM $\left[\frac{pc}{cm^6}\right]$

Table 9.4. Effective recombination coefficients[a]

	Temperature (K)		
$\alpha_{j,i}$ ($cm^3\ s^{-1}$)	5 000	10 000	20 000
$\alpha_{3,2}$ (H α)	2.21×10^{-13}	1.17×10^{-13}	5.97×10^{-14}
$\alpha_{4,2}$ (H β)	5.41×10^{-14}	3.03×10^{-14}	1.61×10^{-14}

[a]Case B recombination has been assumed (see Sect. 9.4.2). H α values are from Ref. [160] and H β values are from Ref. [115]. For the latter reference, means for the densities, 10^2 and 10^4 cm^{-3} are given.

↑ well known, for any 2 lines in an atom, ε_M is the same

$$\frac{\int_\nu I_\nu d\nu \ (j \to i)}{\int I_\nu d\nu \ (k \to m)} = \frac{\nu_{ji}\ \alpha_{ji}}{\nu_{km}\ \alpha_{km}}$$

α Temp

Ex Hα & Hβ

$$\frac{\nu_{32}\ \alpha_{32}}{\nu_{4-2}\ \alpha_{42}} = \begin{bmatrix} \text{table C.1} \\ \text{table 9.4} \end{bmatrix} = \frac{486.132}{656.288} \cdot \frac{1,17 \cdot 10^{-13}}{3,03 \cdot 10^{-14}}$$

$$= 2,86$$

Assume HII region
$T = 10^4\ K$

line ratio = diagnostic to get temperature for HII clouds etc

Table 9.5. Sample line ratios for the hydrogen balmer series[a]

	T_e (K)					
	5000		10000		20000	
	n_e (cm^{-3})		n_e (cm^{-3})		n_e (cm^{-3})	
Line ratio	10^2	10^4	10^2	10^4	10^2	10^4
Balmer: $H\alpha/H\beta$	3.04	3.00	2.86	2.85	2.75	2.74
$H\gamma/H\beta$	0.458	0.460	0.468	0.469	0.475	0.476
$H\delta/H\beta$	0.251	0.253	0.259	0.260	0.264	0.264
$H\epsilon/H\beta$	0.154	0.155	0.159	0.159	0.162	0.163

[a]Ref. [50]. Case B recombination has been assumed (see Sect. 9.4.2).

can form the ratio of any two lines that we observe (results not dependent on broadening effects)

ratio weakly dependent on T for Balmer lines! only changes a few %

once we have T_e => find density (knowing D) (via eq 9.14)

But a few complications

case A : all lines opt thin
case B : Lyman lines (UV) which are optically thick
=> affects the line ratios ~ 3%

Use other line ratios! pick lines optically thin and with stronger temp dependencies

[OIII] & [NII] — square brackets = forbidden lines

5007 — "nebulium" — could not be seen in Earth lab — too high density

$$R_{\rm O} = \frac{I(\lambda 4959) + I(\lambda 5007)}{I(\lambda 4363)} = \frac{7.73\exp[(3.29\times10^4)/{\rm T_e}]}{1+4.5\times10^{-4}\,[n_{\rm e}/({\rm T_e})^{1/2}]} \quad ([{\rm OIII}]) \qquad (9.17)$$

$$R_{\rm N} = \frac{I(\lambda 6548) + I(\lambda 6583)}{I(\lambda 5775)} = \frac{6.91\exp[(2.50\times10^4)/{\rm T_e}]}{1+2.5\times10^{-3}\,[n_{\rm e}/({\rm T_e})^{1/2}]} \quad ([{\rm NII}]) \qquad (9.18)$$

these ratios most sensitive to temp

choose your lines carefully

optical affected by dust — extinction — reddening

- pick lines close to each other
- can also correct for extinction with eg. Balmer line ratios.

RRLs

Radio recombination lines

highest quantum #
transitions: $n \geq 40$

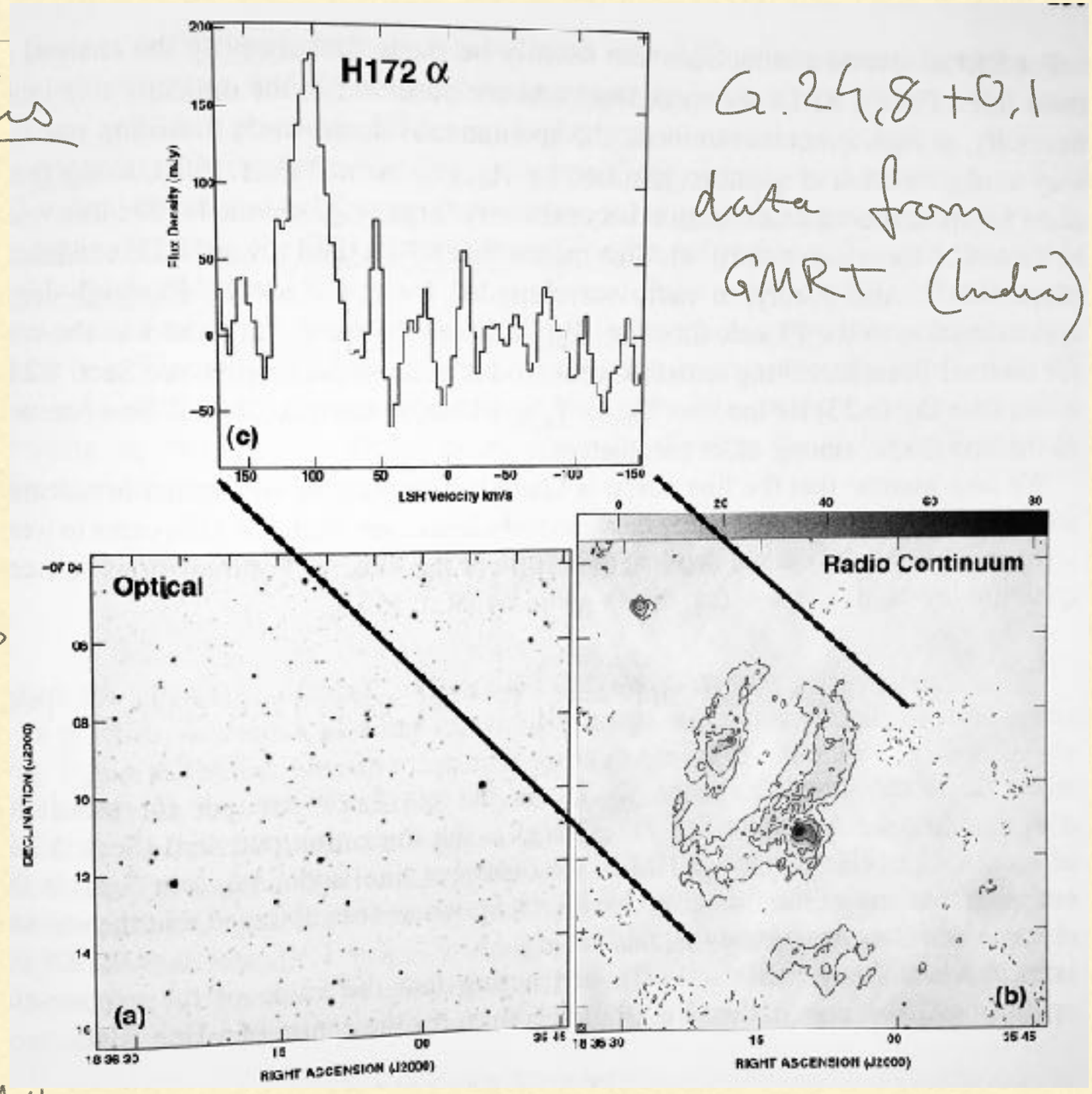
at high n, transitions
close together
⇒ radio >
redwaves

& low probability
for these transitions.
⇒ RRLs weak
many transitions

$n = 766$ Carbon $\nu = 1\,\mathrm{GHz}$

for H $n = 1600$ theorized to be possible

radio not obscured by dust ⇒ RRLs only way to see some regions



G. 24.8 +0.1
data from
GMRT (India)

Fig 9.6

DIG Diffuse ionized gas of MW

lines ⇒ doppler ⇒ distances

(cannot be done with continuum)

Simplifications promised: $\begin{cases} \tau_\nu \ll 1 \\ \text{LTE conditions} \\ h\nu \ll kT \Rightarrow R\text{-}J \end{cases}$

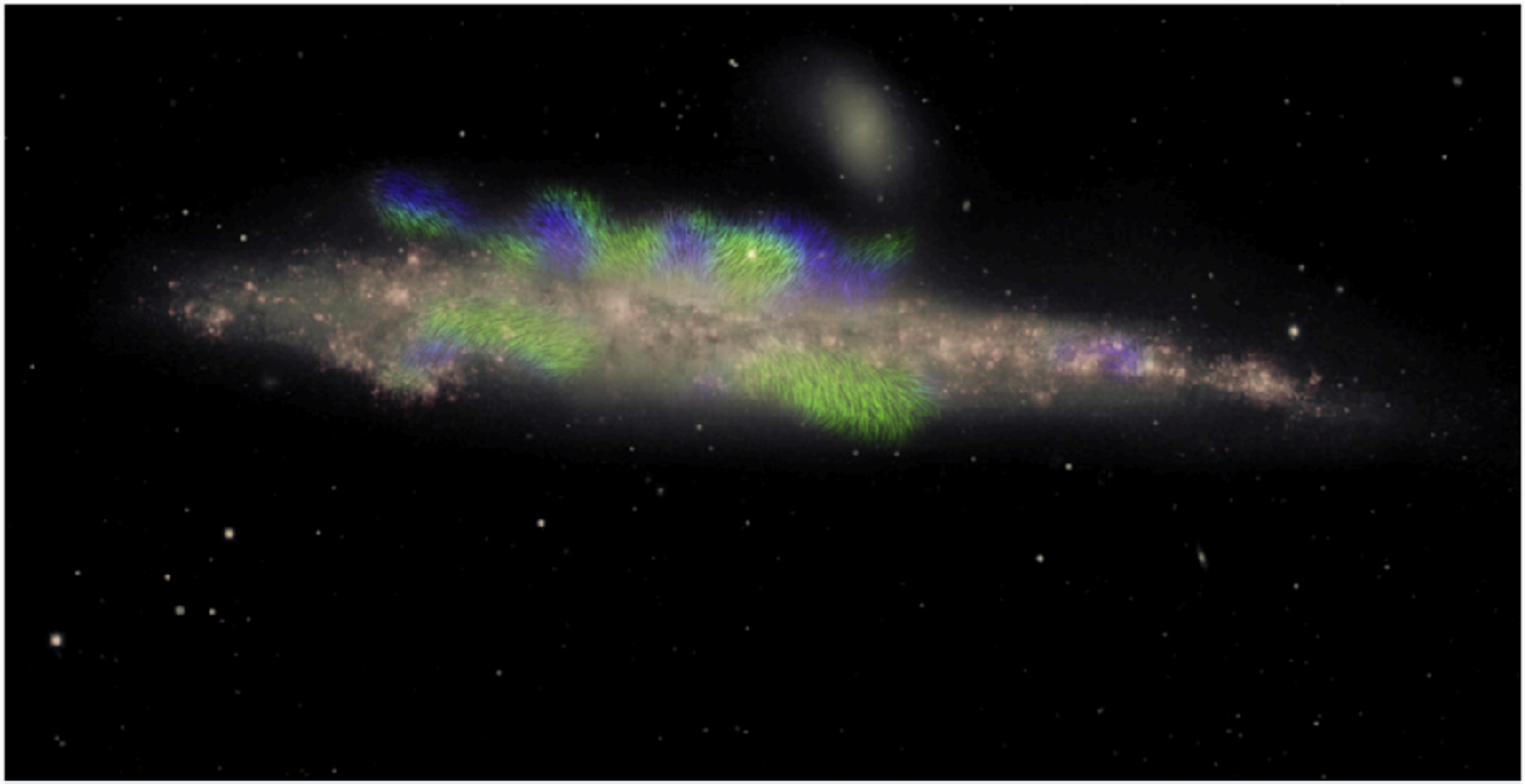
optically thin: ∠Temp & density $T_B = T_e \tau_\nu$

Observe RRL's — superimposed on the continuum radiation — Bremsstrahlung in radio region

⇒ τ & T_B (eq 8.12 & 8.13)

https://public.nrao.edu/news/giant-magnetic-ropes/

IMAGE RELEASE: Giant Magnetic Ropes in a Galaxy's Halo



Credit: Composite image by Jayanne English of the University of Manitoba, with NRAO VLA radio data from Silvia Carolina Mora-Partiarroyo and Marita Krause of the Max-Planck Institute for Radioastronomy. The observations are part of the project Continuum HAlos in Nearby Galaxies -- an EVLA Survey (CHANG-ES). The optical data were from the Mayall 4-meter telescope, collected by Maria Patterson and Rene Walterbos of New Mexico State University. Arpad Miskolczi of the University of Bochum provided the software code for tracing the magnetic field lines.

CHANG-ES XV: Large-scale magnetic field reversals in the radio halo of NGC 4631

Silvia Carolina Mora-Partiarroyo, Marita Krause, Aritra Basu, Rainer Beck, Theresa Wiegert, Judith Irwin, Richard Henriksen, Yelena Stein, Carlos J. Vargas, Volker Heesen, Rene A. M. Walterbos, Richard J. Rand, George Heald, Jiangtao Li, Patrick Kamieneski, Jayanne English

(Submitted on 16 Oct 2019)

NGC 4631 is an interacting galaxy which exhibits one of the largest gaseous halos observed among edge-on galaxies. We aim to examine the synchrotron and polarization properties of its disk and halo emission with new radio continuum data. Radio continuum observations of NGC 4631 were performed with the Karl G. Jansky Very Large Array at C-band (5.99 GHz) in the C & D array configurations, and at L-band (1.57 GHz) in the B, C, & D array configurations. The Rotation Measure Synthesis algorithm was utilized to derive the polarization properties.

We detected linearly polarized emission at C-band and L-band. The magnetic field in the halo is characterized by strong vertical components above and below the central region of the galaxy. The magnetic field in the disk is only clearly seen in the eastern side of NGC 4631, where it is parallel to the plane of the major axis of the galaxy. We detected for the first time a large-scale, smooth Faraday depth pattern in a halo of an external spiral galaxy, which implies the existence of a regular (coherent) magnetic field.

A quasi-periodic pattern in Faraday depth with field reversals was found in the northern halo of the galaxy. The field reversals in the northern halo of NGC 4631, together with the observed polarization angles, indicate giant magnetic ropes (GMRs) with alternating directions. To our knowledge, this is the first time such reversals are observed in an external galaxy.

Comments: 8 pages, 7 figures, accepted to be published in A&A

Subjects: Astrophysics of Galaxies (astro-ph.GA)

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