The mystery of the filamentary structures in the LOFAR data

Isabelle Santos

Marta Alves, Katia Ferrière

IRAP

June 13, 2019

Introduction

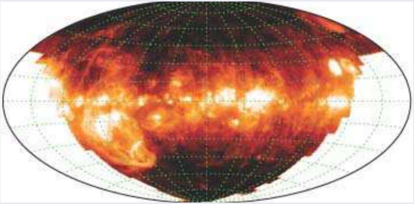

Figure: Ionized gas. Credit: Haffner, 2003.

What is the interstellar medium (ISM)?

- Dust
- Gas
- Magnetic fields

Introduction

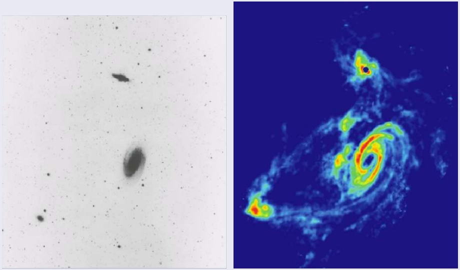

Figure: M81 in visible light (left) and in HI emission (right). Credit: NRAO/AUI.

What is the interstellar medium (ISM)?

- Dust
- Gas
- Magnetic fields

Why study the Interstellar Medium?

- Galaxy dynamics

Introduction

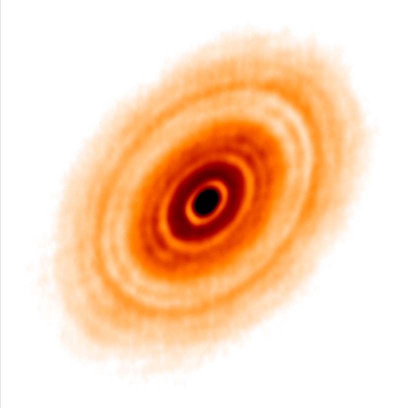

Figure: Protoplanetary disk HL Tau seen by ALMA. Credit: Carrasco-Gonzalez et al.

What is the interstellar medium (ISM)?

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Why study the Interstellar Medium?

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- star and planet formation

Introduction

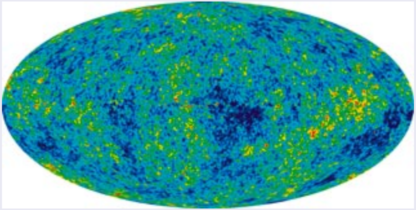

Figure: Cosmic Microwave Background. Credit: NASA.

What is the interstellar medium (ISM)?

- Dust
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Why study the Interstellar Medium?

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- cosmic background

Introduction

Figure: Faraway galaxies. Credit: HST/NASA.

What is the interstellar medium (ISM)?

- Dust
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Why study the Interstellar Medium?

- Galaxy dynamics
- star and planet formation
- cosmic background
- ”nearby” laboratory

Introduction

Draco Nebula

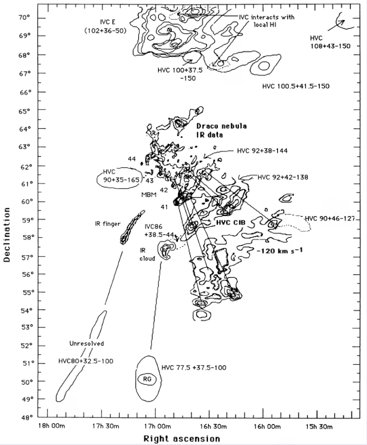


Figure: Vershuur, 1990.

- Intermediate Velocity Cloud
- High latitude
- Multiple observations:
  - ionized, neutral and molecular gas, dust

Introduction

Draco Nebula

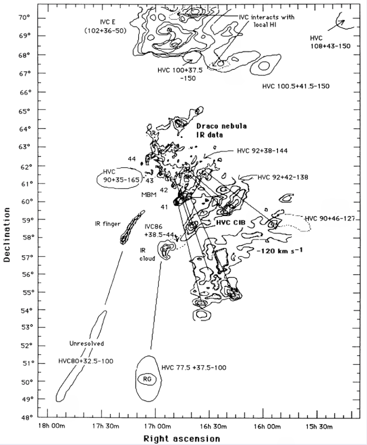


Figure: Vershuur, 1990.

- Intermediate Velocity Cloud
- High latitude
- Multiple observations:
  - ionized, neutral and molecular gas, dust
  - magnetic fields?

Faraday Tomography

Plane polarized light in a medium with circular birefringence

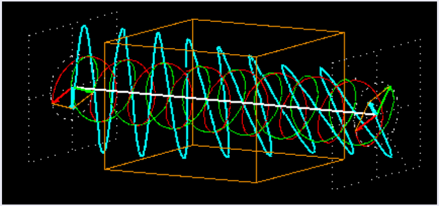
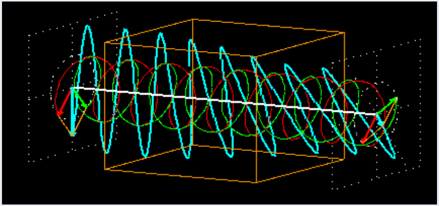


Figure: cddemo.szialab.org

- plane polarized light source

Faraday Tomography

Plane polarized light in a medium with circular birefringence



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- plane polarized light source
- refraction index is different for left and right circularly polarized light
- plane polarized light is the superposition of left and right circularly polarized light

Faraday Tomography

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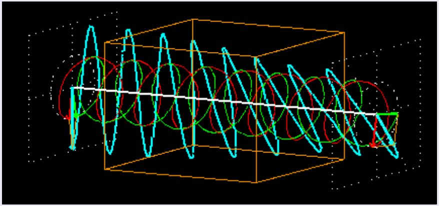

Figure: cddemo.szialab.org

- plane polarized light source
- refraction index is different for left and right circularly polarized light
- plane polarized light is the superposition of left and right circularly polarized light
- rotation of the plane of polarization of plane polarized light for observer

Faraday Tomography

Definition

Rotation Measure

$$\Delta\theta = RM \cdot \lambda^2 \tag{1}$$

Faraday Tomography

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Rotation Measure

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$$RM = \mathcal{C} \int_0^L n_e B_{\|} \, ds \tag{2}$$

Faraday Tomography

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Definition

Faraday depth

$$\phi = \mathcal{C} \int_0^{z} n_e B_{\parallel} \, ds \tag{3}$$

Faraday Tomography

Definition

Rotation Measure

$$\Delta\theta = RM \cdot \lambda^2 \tag{1}$$

$$RM = \mathcal{C} \int_0^L n_e B_{\parallel} \, ds \tag{2}$$

Definition

Faraday depth

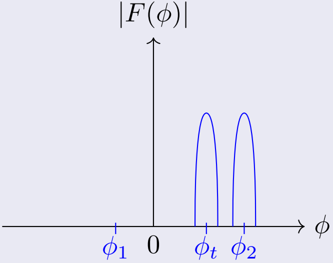
$$\phi = \mathcal{C} \int_0^z n_e B_{\parallel} \, ds \tag{3}$$

$$P(\lambda^2) = \int_{-\infty}^{\infty} \textcolor{red}{F(\phi)} \exp^{2i\phi\lambda^2} \, d\phi \tag{4}$$

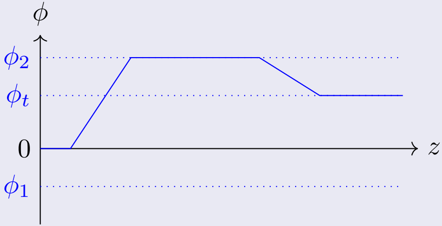
Faraday Tomography

Interstellar medium

Polarized emission



Faraday depth



$$\phi_t = \phi_1 + \phi_2$$

Faraday Tomography

LOFAR

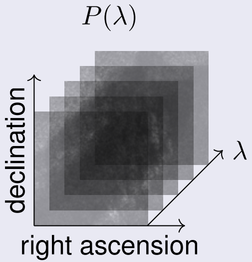
- Low-Frequency Array

Faraday Tomography

LOFAR

- Low-Frequency Array

Faraday tomography on LOFAR data

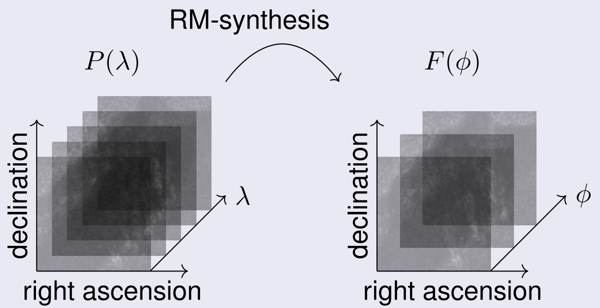


Faraday Tomography

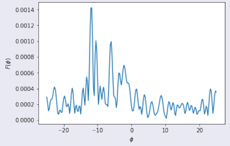
LOFAR

- Low-Frequency Array

Faraday tomography on LOFAR data

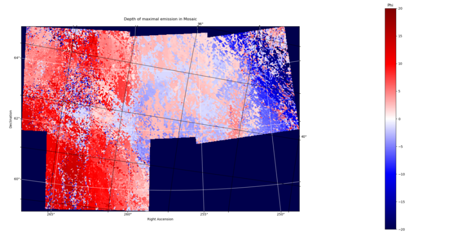


Emission $F(\phi)$ at a given pixel



Depolarization canals

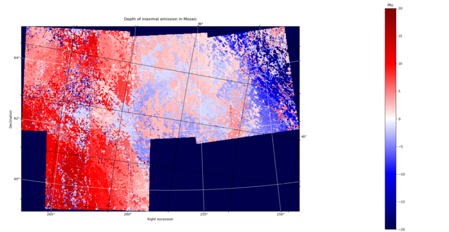
Depth of maximal emission



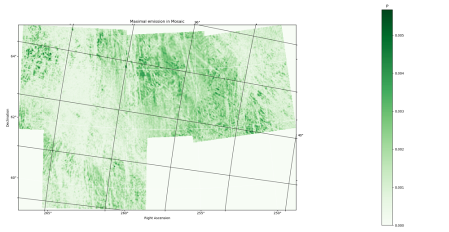
- two distinct regions

Depolarization canals

Depth of maximal emission



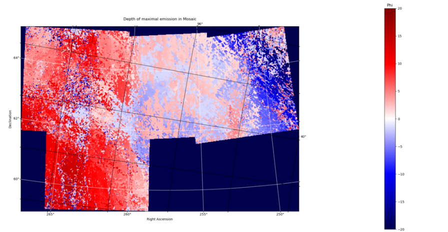
Maximal emission



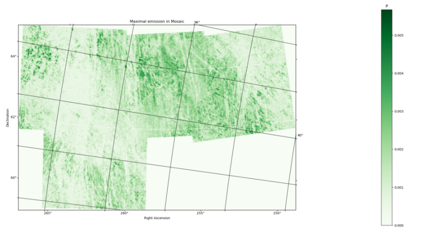
- two distinct regions
- ”holes” in emission: canals

Depolarization canals

Depth of maximal emission



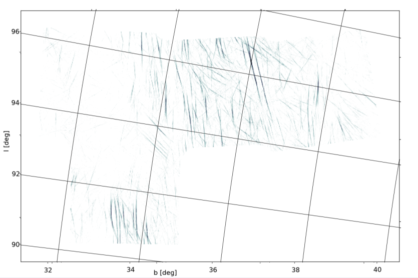
Maximal emission



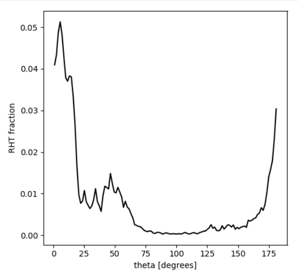
- two distinct regions
- ”holes” in emission: canals
- two canal orientations

Depolarization canals

RHT backprojection



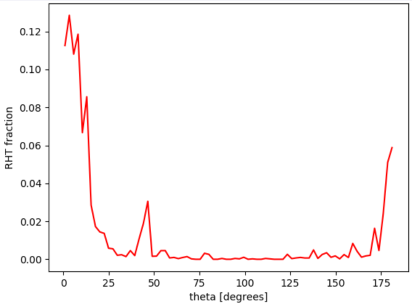
Canal distribution



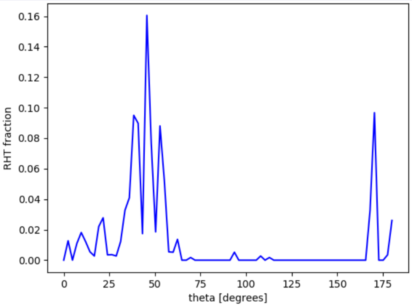
- Rolling Hough Transform
- two peaks in canal distribution

Depolarization canals

At positive Faraday depth



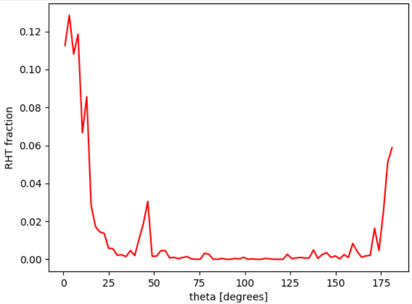
At negative Faraday depth



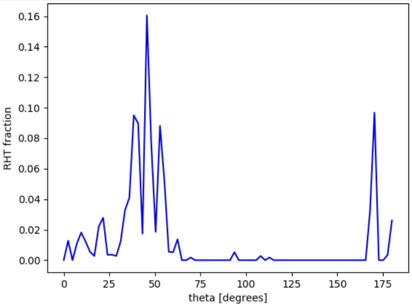
- Canal orientation is correlated with Faraday depth of emission maximum

Depolarization canals

At positive Faraday depth



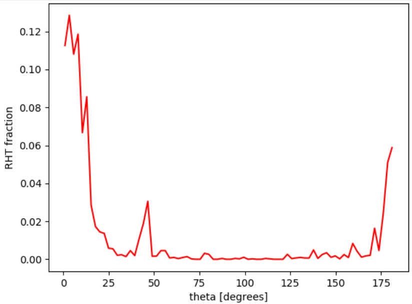
At negative Faraday depth



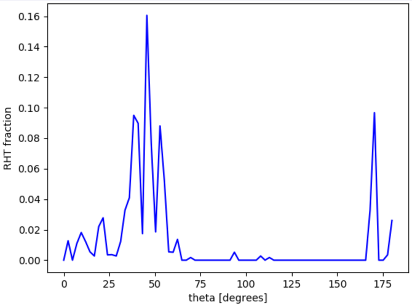
- Canal orientation is correlated with Faraday depth of emission maximum
- Two Faraday screens

Depolarization canals

At positive Faraday depth



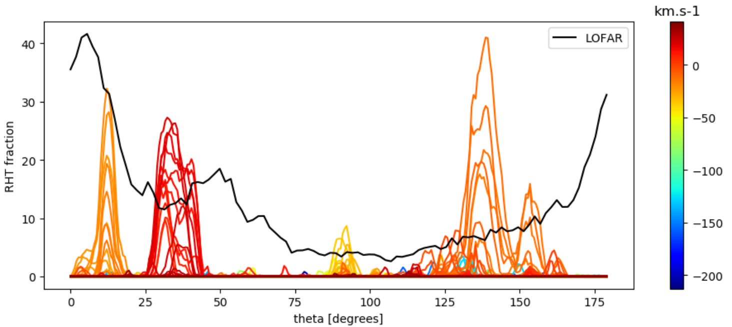
At negative Faraday depth



- Canal orientation is correlated with Faraday depth of emission maximum
- Two Faraday screens
- At what distance are the Faraday screens ?

HI filaments

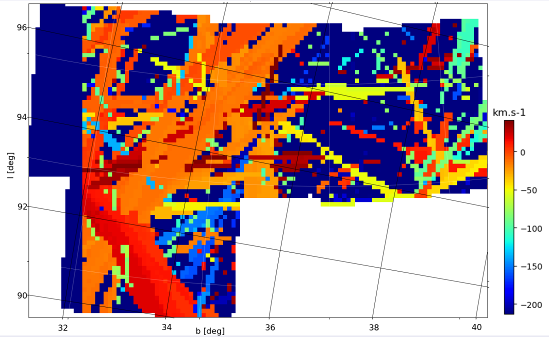
Filament distribution



- linear structures in HI emission at low velocities
- no clear alignment between LOFAR canals and HI filaments
- near alignment around 30° to 50° ?

HI filaments

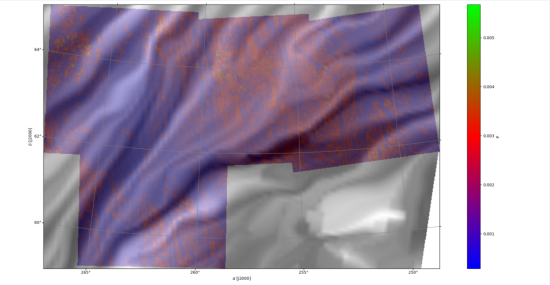
HI filaments



- filaments with similar orientation are not along the same line of sight

Planck data

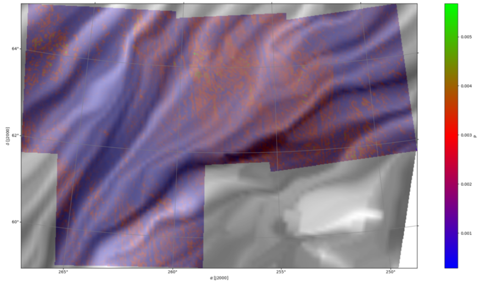
Planck LIC map



- dust polarization as a proxy for magnetic field orientation

Planck data

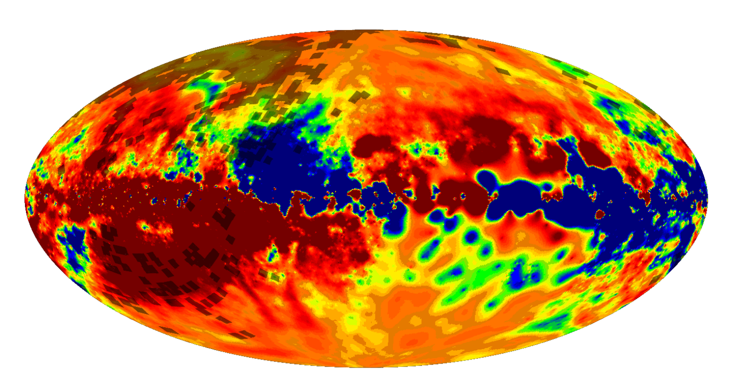
Planck LIC map



- dust polarization as a proxy for magnetic field orientation
- no alignment with depolarization canals

Galactic rotation measure

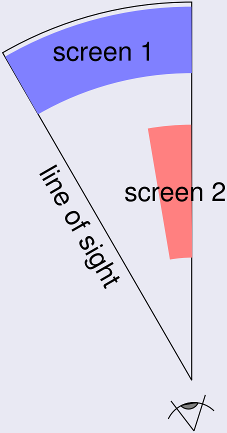
Rotation measure (Oppermann, 2015)



- Inversion of the depth of maximal emission
- Probing the entire line of sight with LOFAR

Conclusion

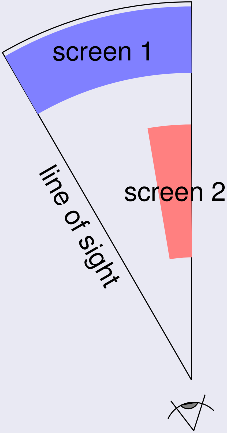
ISM model along the line of sight



- Two screens

Conclusion

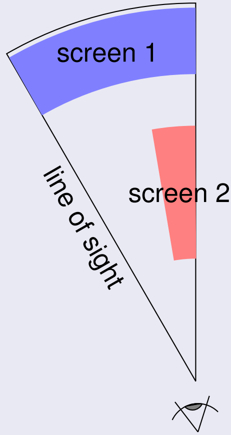
ISM model along the line of sight



- Two screens
- one with negative Faraday thickness

Conclusion

ISM model along the line of sight



- Two screens
- one with negative Faraday thickness
- up to the edge of the galaxy

Conclusion

Conclusions

- two Faraday screens with Faraday thicknesses of opposite sign

Conclusion

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- two Faraday screens with Faraday thicknesses of opposite sign
- no HI filament / depolarization canal alignment

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- two Faraday screens with Faraday thicknesses of opposite sign
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- position along the line of sight remains an open question

Conclusion

Conclusions

- two Faraday screens with Faraday thicknesses of opposite sign
- no HI filament / depolarization canal alignment
- position along the line of sight remains an open question
  - link with Draco Nebula?

Conclusion

Directions for future work

- In neighboring fields

Conclusion

Directions for future work

- In neighboring fields
  - Draco Nebula

Conclusion

Directions for future work

- In neighboring fields
  - Draco Nebula
  - Draco Nebula surroundings

Conclusion

Directions for future work

- In neighboring fields
  - Draco Nebula
  - Draco Nebula surroundings
- Elsewhere

Conclusion

Directions for future work

- In neighboring fields
  - Draco Nebula
  - Draco Nebula surroundings
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  - Cygnus Loop

Conclusion

Directions for future work

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  - Draco Nebula
  - Draco Nebula surroundings
- Elsewhere
  - Cygnus Loop
  - HI filaments / depolarization canals alignment

Thank you

Abell 2218, NASA/HST

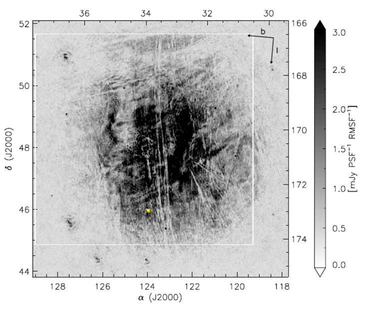


Figure: Jelić, 2015

Angular distribution of tracers in 3C 196

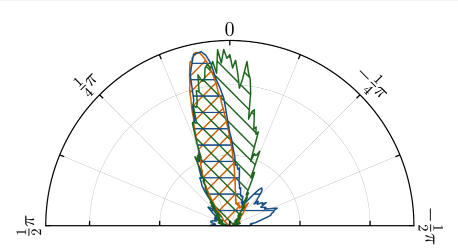


Figure: Jelić, 2018

- three aligned tracers
  - straight depolarization canals
  - HI filaments
  - plane-of-sky magnetic field

LOFAR fields around the Draco Nebula

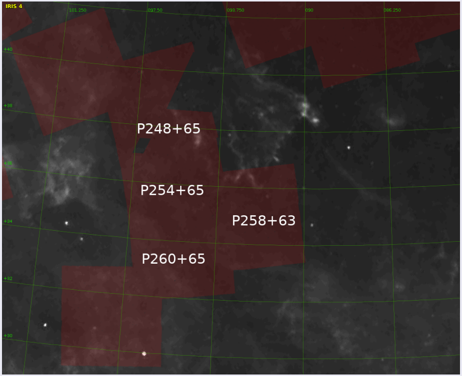


Figure: IRAS/LOFAR

Draco Nebula in soft X-rays

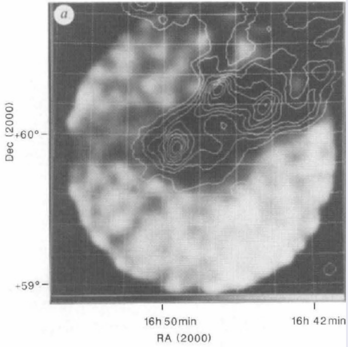
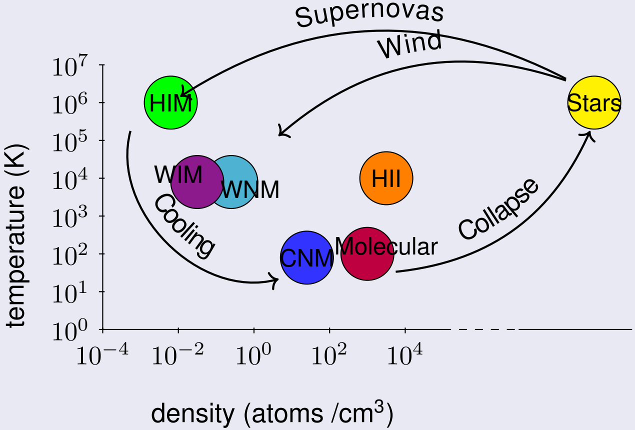


Figure: ROSAT, D. Burrows

- Draco Nebula cast a shadow on background emission
- White lines are contours of visible light

Phases of the Interstellar Medium



- 7000 antennas
- 120 MHz to 168 MHz
- 12.2 kHz resolution
- 4° primary beam
- 5″ maximum resolution
- 2% of the sky covered to date

The Draco Nebula has not yet been observed by LOFAR but will be.

LOFAR core station

Figure: LOFAR