Measuring Cosmic Radio Emission

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15.11.2002
Radio Astronomy

Radio radiation

\[ E: \ 4.2 \text{meV} \rightarrow 41.4 \text{peV} \]
\[ \nu: \ 1 \text{THz} \rightarrow 10 \text{kHz} \]
\[ \lambda: \ 300 \mu m \rightarrow 3 \cdot Tm \]

The sources of radiation

Accelerated electric charges
Atoms
Molecules
Ions
Synchrotron radiation

For extremely relativistic particles:
opening cone: \[ \theta = \frac{m_e c^2}{E} = \frac{1}{\gamma} \]
The spectrum has its maximum at:
\[ \nu_m [GHz] = 4.7 \cdot 10^{-3} B_\perp \left[10^{-10} T\right](E [GeV])^2 \]

At a characteristic galactic magnetic field of \(10^{-10} T\):

| \(\nu_{\text{max}} [GHz]\) | \(10^{-2}\) | 1 | \(10^2\) |
|\(\lambda_m\) | 30 m | 30 cm | 3 mm |
| \(E_e [GeV]\) | 1.5 | 15 | 1500 |

The time in which an electron loses half of its energy to synchrotron radiation:
\[ t_{1/2} [a] = 5.7 \cdot 10^8 \left(B\left[10^{-10} T\right]\right)^{-3/2} \cdot (\nu_m [GHz])^{-1/2} \]
e.g. the Crab nebula:
\(B \sim 10^{-8} T\)
\(\nu_m \sim 1\ GHz\quad 10^9\ GHz\ (=X)\)
\(t_{1/2} \sim 600000\ a\quad 20\ a\)

The synchrotron radiation is polarized
The spectrum of electrons in many sources has a power law $\sim E^{-p}$.

The resulting Synchrotron spectrum is then also a power law:

$$I(\nu) = \left(\text{const}\right) \cdot \kappa B^{(p+1)/2} \nu^{-(p-1)/2}$$
Black-body radiation

The intensity which is emitted by a black-body (Planck’s formula):

\[ I_\nu(T) = B_\nu(T) = \frac{2\hbar \nu^3}{c^2} \frac{1}{e^{\frac{\hbar \nu}{kT}} - 1} \]

With the two limiting cases:

Wien’s Law: \( \frac{\hbar \nu}{kT} \gg 1 \): \( B_\nu(T) \approx \frac{2\hbar \nu^3}{c^2} e^{-\frac{\hbar \nu}{kT}} \)

Rayleigh-Jeans: \( \frac{\hbar \nu}{kT} \ll 1 \): \( B_\nu(T) \approx \frac{2\nu^2 kT}{c^2} \)
Atomic and molecular levels:

Neutral hydrogen
The two hyperfine structure levels of the ground state $1s^2 S_{1/2}$:

$$\Delta E = 5.9 \cdot 10^{-6} \text{eV}$$
$$\lambda_0 = 21.1 \quad \nu_0 = 1420.4 \text{GHz}$$

CO molecule (rotational level):
$$\Delta E = 4.8 \cdot 10^{-4} \text{eV}$$
$$\lambda_0 = 2.6 \text{mm} \quad \nu_0 = 115.27 \text{GHz}$$

Plasma emissions:
Oscillation
free-electron -Laser
Very intensive, because of coherent emission:

Maser:
For example $OH, H_2O$
Propagation of radio radiation in the ISM

Dispersion:
\[ \omega_p = \sqrt{\frac{4\pi n_e e^2}{m}} \quad n(\omega) = -\sqrt{\frac{\omega_p^2}{\omega^2} - 1} \quad \rightarrow \quad \text{group velocity: } v_{gr} = v(\omega) \]

Scattering:
The irregularities where the radio radiation is scattered must be of the order of the wavelength:

It is scattered on regions with different electron densities

Faraday rotation
When radiation traverses an interstellar magnetic field, the plane of polarization of the radio radiation will be rotated by angle \( \Psi \):

\[ \Psi = \lambda^2 \cdot RM \]

\[ RM = 8.1 \cdot 10^3 \cdot \int_0^L n_e B_\parallel \, dl \]
What do we measure and what can be derived from that

Intensity and Distribution (Maps)

Continuous spectra:
From that we can distinguish the kind of radiation (thermal; nonthermal radiation)

The line spectra:
Intensity of lines \( \rightarrow \) composition of the target \( \rightarrow^{12} CO \ , \ {^{13}CO} , \ {^{12}C/^{13}C} \) ratio

\[
\frac{V}{c} \ll 1 : \\
\nu' = \nu \left(1 + \frac{V}{c}\right) \quad \text{Doppler effect}
\]

So from shifts of the lines one can get the velocity of the matter and from the strength of the lines one can derive the density

Polarisation
From the Faraday effect one can get the longitudinal magnetic field in the IMS

Time:
Variable sources, Pulsar emission
Historical sources

Haslam at 408 Mhz
1982

Centaurus A:

Virgo A:
VLA image scale is 80 kpc

80 kpc

Sun:
1995 at 37 GHz

Virgo A
74 MHz, 60” VLA 1998
Galaxy

Neutral hydrogen:

The 21.1 cm line of neutral hydrogen
Milky Way

Surveys of the neutral hydrogen in the Milky Way show the spiral structure:
Radio radiation of the CO-molecule:

*carbon monoxide molecule*

\[ \text{carbon} \quad \text{oxygen} \quad \text{2.6 mm radiation} \]

Molecular hydrogen regions in the Milky Way observed at 115 Ghz
CO-surveys of the Milky Way
The center of the Milky Way

The SgrA-complex:
VLA at 20 cm (synchrotron)
Galactic Center

HII-regions: SgrA West:
(free-free emission)

Sgr a West at 6 cm ionized gas
Supernova remnants

The Crab Nebula:

VLA at 74 MHz: diameter: 6’

Pacini: Crab nebula gas ejected at by supernova explosion 1054. Centuries after the explosion is still filled with relativistic electrons.

Energy source: slowing- down of neutron star
Maser

Unusually high intensities are found for the lines of the OH radical at $\lambda = 18\text{ cm}$

In terms of radiation temperature they correspond to $10^{12} K$ to $10^{15} K$

The lines are exceedingly sharp and are emitted by a very compact sources

This can only be explained by a maser amplification mechanism

The “pump process” is not in detail understood

Stimulated emission is produced by a radiation field at the same frequency

Maser lines from other molecules are also observed $H_2O$ at $\lambda = 1.35\text{ cm}$

Also: $SiO$, $H_2CO$
The sun as a source of radio radiation

The sun at radio radiation of 20 cm

Sunspots:
Temperature: 4000 C
Sun: 6000 C
Centers of magnetic field

$B \sim 10^{-1}$ T
relativistic electrons

Synchrotron and Plasma emissions
Comparison of Optical and Radio Solar Flares

Optical View

Radio Pattern
Extragalactic Systems

M81

21 cm wavelength: optical
The Andromeda galaxy (M31):

Radio image at 21 cm

Optical image
Active Galaxies

Cygnus A: One of the strongest radio sources in the sky

At 6 cm: 200 kpc

Two jets are emitted at the center

Process: Synchrotron emission

energetic electrons in magnetic fields
Centaurus A at the 6 cm radio radiation:
Quasars

3C273 taken from MERLIN at 408 Mhz
Quasar 0836+710

Radiointerferometry image at 3.6 cm

blob moves with apparent superluminal velocity

Rel. Deklination

Rel. Rektaszension

Quasar 0836+710

\[
\beta_\perp = \frac{\beta \sin \delta}{1 - \beta \cos \delta}
\]

Lorentz factor:

\[
\gamma \approx 5-10
\]
Cosmic Background Radiation

COBE

Frequencies: 31.5, 53 and 90 GHz
The COBE spectrum
Boomerang

Dec. 29.1998
Flight time: 260 hours
Height: 40km

focal plane where the optics, filters and detectors are located
Boomerang

Frequencies: 90, 150, 240 and 410 GHz
Map Description in terms of spherical functions:
\[ \Delta T/T \sim \text{Sum}(\alpha_{lm} \cdot Y_{lm}(\delta,\phi)) \]

\[ C_1 \sim |\alpha_{lm}|^2 \]

strength of fluctuations on angular scale \( \delta \sim 180^\circ/l \)

\( \alpha \sim 1^\circ \quad l \sim 200 \)
Launch ~2007

http://sci.esa.int/plank