

8.1 Radio Emission from Solar System objects

8.1.1 Moon and Terrestrial planets

At visible wavelengths all the emission seen from these objects is due to light reflected from the sun. However at radio wavelengths there is very little reflected sunlight so the radio emission observed from the planets is dominated by thermal emission. This emission is related to the surface temperature of these bodies. Figure 1 contains a measurement of Venus made with the Haystack 37-m telescope. The first one shows scans of the planet made in azimuth and elevation. The peak of the scans corresponds to the antenna temperature of the planet. This temperature can be converted to a brightness temperature by scaling it with the aperture efficiency of the system at this frequency.

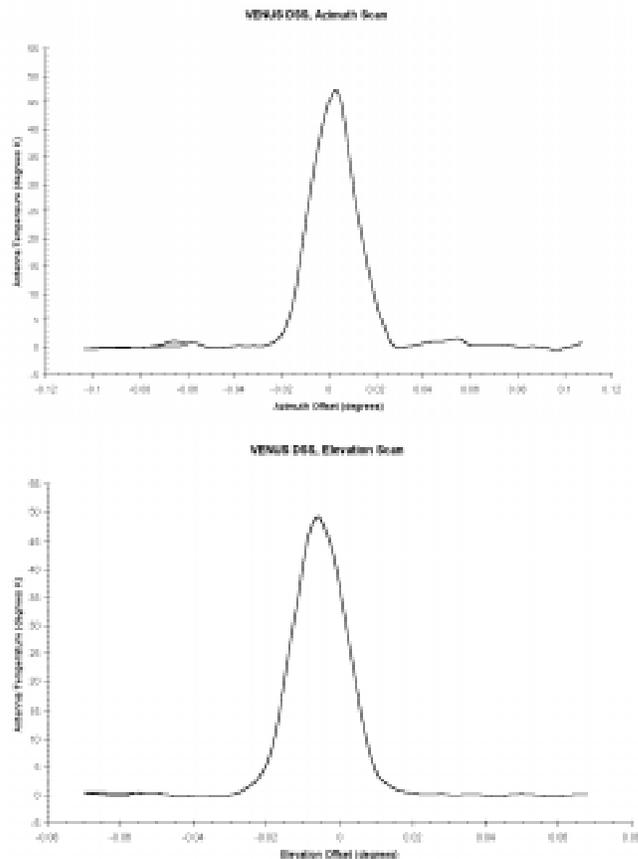


Figure 1

Venus has thick cloud layers that reflect light very well. At infrared wavelengths these clouds are opaque and the temperature measured at these wavelengths is only about 225K. However measurements at radio wavelengths imply a surface temperature of about 700 K. At the shorter

radio wavelengths (< 3 cm) the atmosphere becomes opaque again and the measurements result in lower temperature determinations.

The emission from the moon is also thermal. At infrared wavelengths there are variations correlated to the lunar phase which are due to solar heating. At centimeter wavelengths this variation is much less. This is because the radio emission (which is still thermal) arises from below the surface. The material below the surface is heated by conduction and the variations lag behind the solar heating. The variations are also not as extreme. Figure 2 is a beamswitched observation of the moon made with the Haystack Small Radio Telescope (SRT).

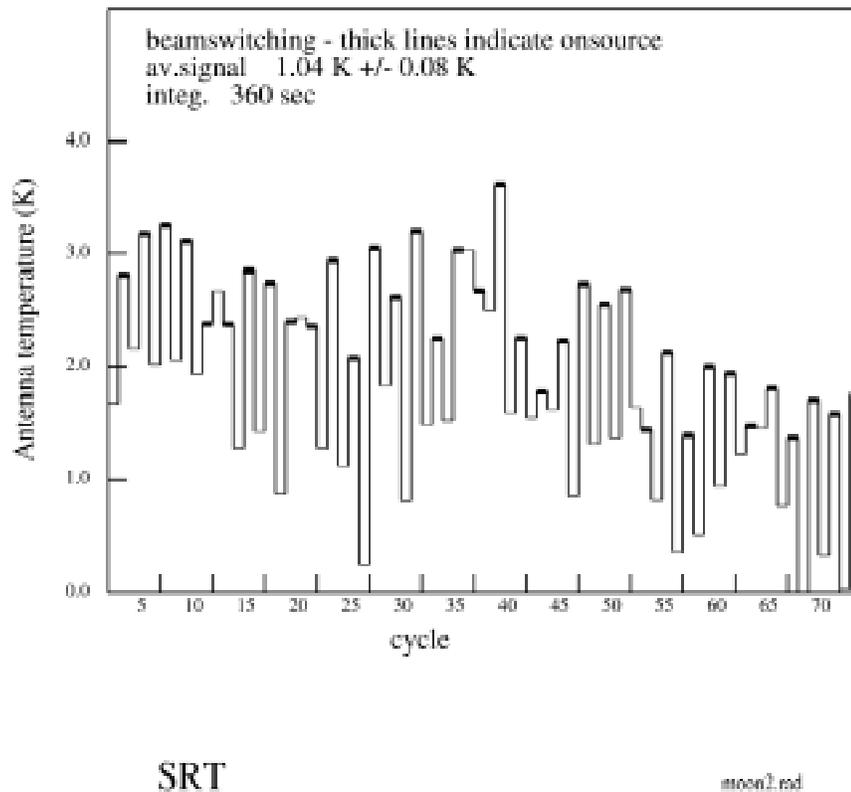


Figure 2

8.1.2 Jovian planets

The Jovian planets are much further from the sun and consequently are colder. Jupiter, however, is a strong radio emitter at the long ($> 10\text{cm}$) radio wavelengths. At shorter wavelengths (around 3 cm) Jupiter has a brightness temperature of around 140 K which is consistent with infrared measurements. However at longer wavelengths the temperatures are of the order of a few thousand degrees. These high temperatures come from a non-thermal source namely synchrotron emission from the strong magnetic field of the planet. Jupiter also has some strongly varying radio emission at long radio wavelengths. The source of this emission has been found to be non-thermal cyclotron emission. This arises from electrons spiraling in Jupiter's magnetic field. The variation is caused by the fact that the origin of these electrons are the volcanoes and geysers on the surface of Io.

Radio emission from the other Jovian planets has been found to be mainly thermal. The emission arises mainly from the cloud tops of the planet atmospheres and shows that the temperatures drop the farther the planet is from the sun.

8.1.3 The Sun

Radio emission from the sun arises from several different phenomena and can be divided into three main components – 1) the quiet sun component, which is always present, 2) the slowly varying component and 3) the active sun component which is caused by sunspots and flare activity.

The quiet sun component of the radio emission is from thermal emission from the hot ionized gas. In order to understand from which part of the sun's atmosphere this emission arises, one needs to understand the main opacity source at radio wavelengths. (The opacity is a measure of how much a wave gets absorbed as it travels through a medium). The main source of opacity in the sun's atmosphere (the photosphere, chromosphere and corona) at radio wavelengths comes from electrons. The bulk of the emission arises from the region where the opacity, τ , is near 1, since at higher optical depth regions cannot be penetrated and the low optical depth regions do not produce enough emission. At visible wavelengths this happens at the photosphere where the temperature is about 6000 K and hence the sun appears as a blackbody with that temperature. At a frequency of 100 GHz (wavelength 0.3cm) the emission originates at the same height in the photosphere and the sun appears as a 6000 K blackbody. But at a frequency of 1.4 GHz (wavelength of 21 cm) the emission originated from the top of the

chromosphere and is seen as a blackbody of temperature of about 100,000 K. And at longer wavelengths (300 cm or frequency of 0.1 GHz) the emission arises from the corona and is a 2 million K blackbody. All this also means that the size of the sun measured at the different wavelengths will vary.

The other two components are related to the sunspot activity on the sun. The slowly varying component is also thermal in origin and arises from the region above the sunspots where the electron density is higher. The blackbody temperature of these regions can be as high as 2 million K. Thus the regions above the sunspots can contribute more radio emission than the total area without sunspots and increase the total radio flux relative to the quiet sun. So the change in the total radio flux is dependent on the total number of sunspots. The radio flux density then follows the 11 year sunspot cycle. Figure 3 shows an image of the sun made with the Haystack 37—m telescope at a frequency of 21 GHz (wavelength of 1.3 cm).

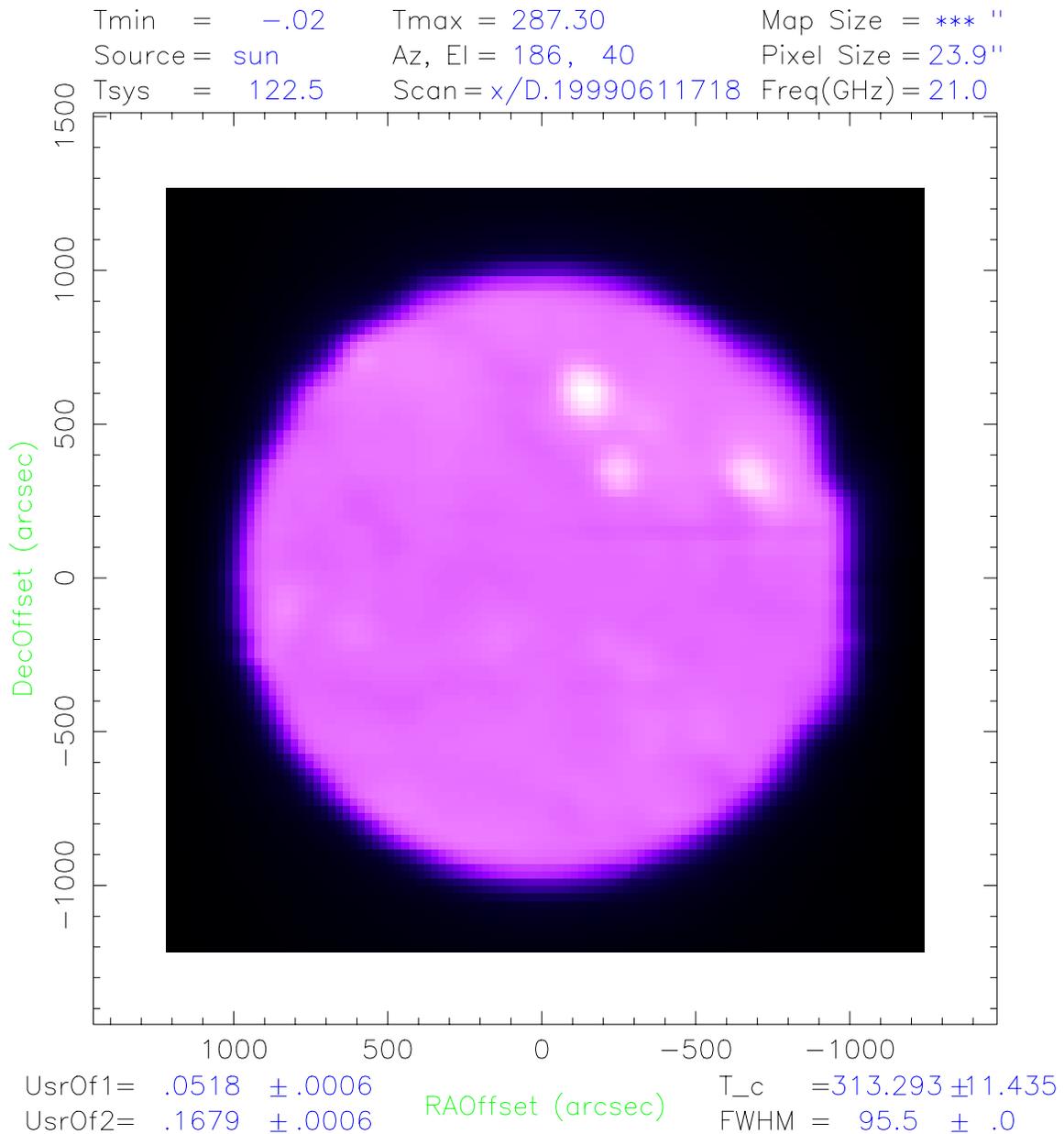


Figure 3

8.2 Stars

The sun is a star and a strong source of radio emission. Most ordinary stars are expected to emit radio waves since they are thermal sources. However, the majority of the radio emission from stars is undetectable since they are far away and the signals are too faint. There is a class of objects known as “radio stars” that emit radio waves although all radio stars do not fall into one category. Many of these stars generate radio emission in strong winds of gas blowing out of the star or in ejected spherical envelopes expanding out from the star’s surface. There is also a class of binary stars that have radio

emission arising from the interaction of their magnetic fields. There is also a category of stars that show flare behavior. It is thought that these are very young stars that are ejecting matter in the form of minor jets.

Most of the strong radio emission comes from stars that are either very young or very old. When stars form they go through phases of mass ejection and interaction with the surrounding medium. One such example are HII regions. These are not direct observations of the star but of the region of ionized hydrogen that is caused by UV radiation from the young star ionizing the gas around it. In many cases, the radio emission from the HII region is the only way of detecting these young stars since they are embedded deeply in the gas clouds from which they are born and hence the optical emission cannot get out. Figure 4 shows an example of an HII region. The grey scale image is an infrared image of an HII region that has a bow-shock appearance. The overlaid contours in the first and third panels corresponds to emission from the molecules CS and C18O. The second panel of contours corresponds to continuum emission at a frequency of 97 GHz.

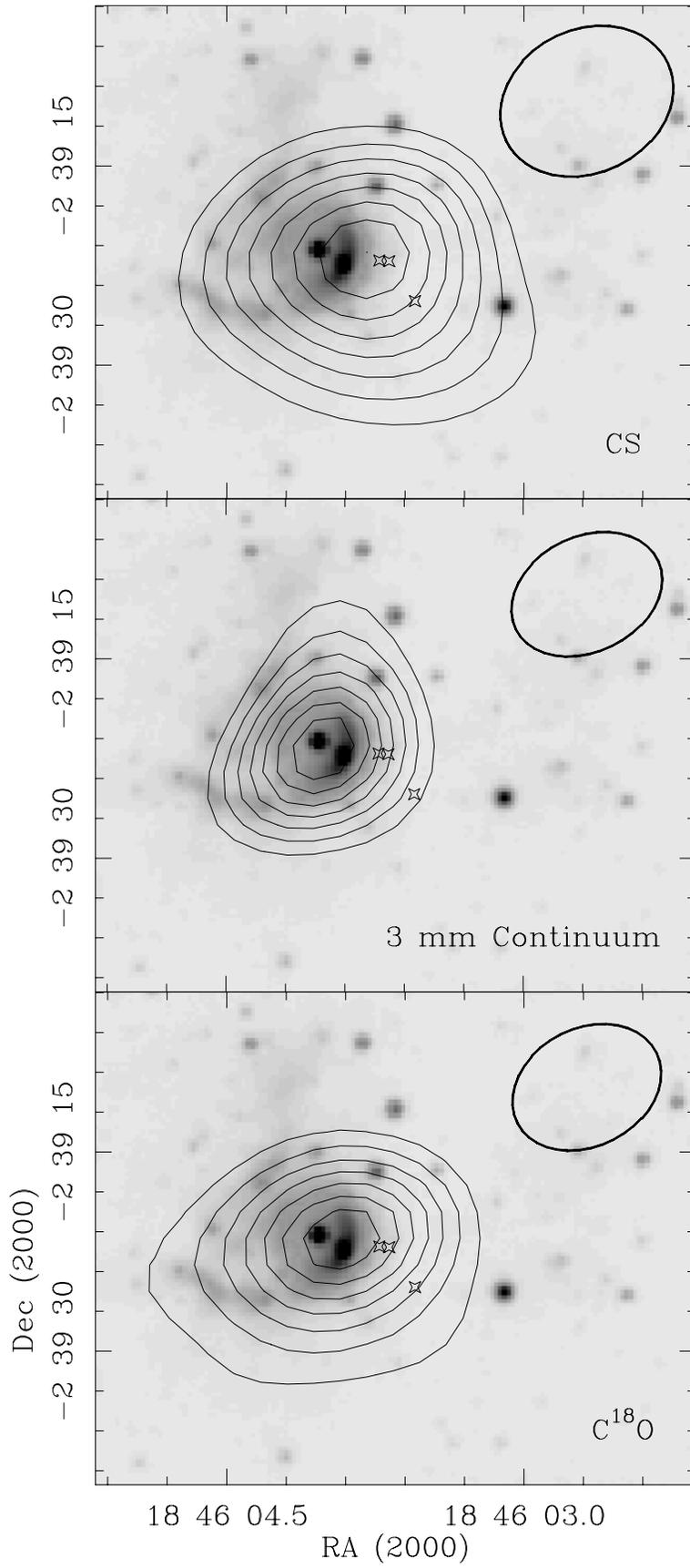


Figure 4

Stars at the end of their life emit radio emission in various ways. One of the exciting discoveries in radio astronomy came from the discovery of pulsars. Pulsars are now known to be neutron stars that spin rapidly and emit radio signals in highly directed beams. As these beams sweep across the direction of the earth, radio telescopes pick them up as a repeating signal. The radio emission mechanisms for these pulsar beams is related to synchrotron emission which is caused by the acceleration of relativistic electrons by a magnetic field. The periodicity is caused by the fact that the magnetic field axis is not coincident with the rotation axis.

When large stars reach the end of their life, they can explode in supernova events. The ejected material then interacts with the surrounding medium. This leads to the formation of “supernova remnants” which also are strong sources of radio emission. What is left behind is a neutron star. An example of a supernova remnant is the Crab nebula (Figure 5).

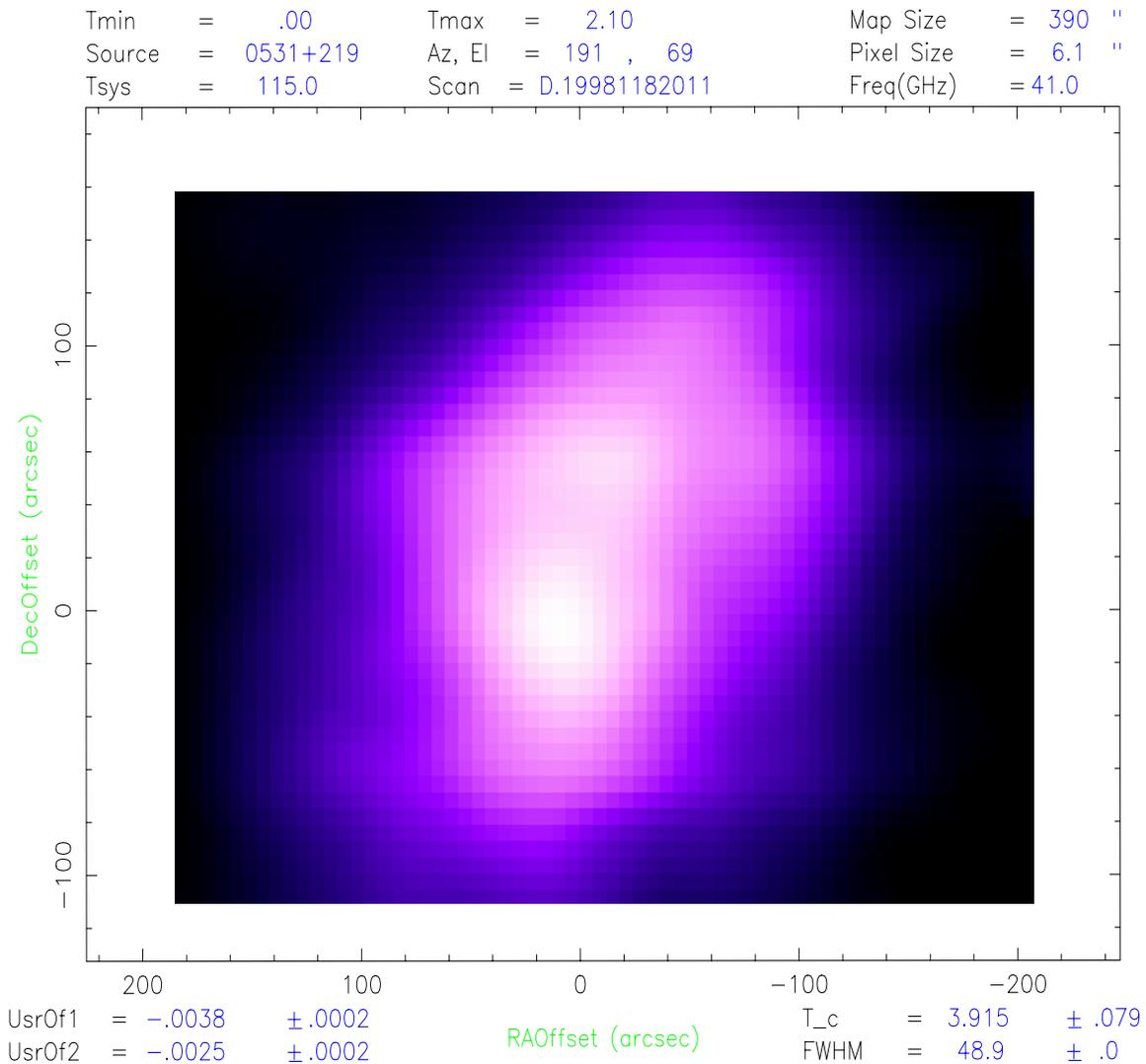


Figure 5

8.3 Interstellar Clouds

A substantial fraction of the gas in the interstellar medium is in molecular form. This gas is in the form of dense, cold "molecular clouds". This component of the interstellar medium is very closely connected with star formation. The molecules in these clouds are excited by collisions and they spontaneously emit producing spectral lines. These spectral lines occur at discrete frequencies that, at radio wavelengths, are governed by the rotation of the molecule.

Radio astronomy was instrumental in the discovery of more than a 100 interstellar molecules and more and more complex molecules are still being discovered. The reason that complex molecules can exist in these molecular clouds without being destroyed by UV radiation from stars is that the clouds

contain large amounts of dust grains that absorb the UV radiation and shield the molecules from photo-destruction. Molecules from simple diatomic ones such as CO, CS, SiO, SO etc to more complex ones such as ethanol, methanol, cyanoacetylene, etc have been detected toward these molecular clouds. The molecular spectra contain substantial information about the physical and chemical environment of these clouds. The velocity of the lines gives information about the motion of the clouds with respect to the solar neighborhood. The line widths measure the internal motion of the gas within the clouds from Doppler motions. The strength of the line and the ratio of information from several different transitions can be used to measure the column density of the gas, the temperature and the density. The density of molecular hydrogen, whose rotation cannot be measured directly, can be calculated from the strength of the spectral lines. Finally, the size and mass of the molecular cloud can be derived by mapping the extent of the molecular emission. Figure 6 shows the emission from a cold, dark cloud in the Taurus region (called TMC-1) in three transitions of the HC₃N molecule. Combining the information from these three transitions can be used to derive the molecular hydrogen density in the cloud.

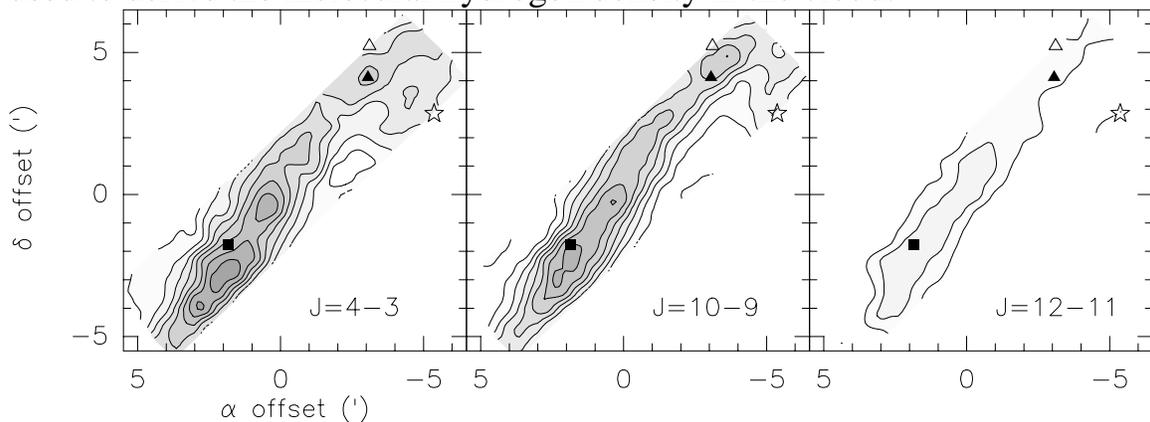


Figure 6

Combining the information from several molecular species one can also study the chemical processes in these clouds. Hence molecules are a powerful tool that is available to scientists to study molecular clouds and through them the process of star formation.

8.4 Milky Way

A component of the radio emission from the Milky Way comes from the spin flip transition of the hydrogen atoms in the interstellar medium. This spectral line arises from the fact that the electron and the proton in the hydrogen atom have a particular direction of spin. The energy of the

situation where the spins are aligned is different from that when the spins are in opposite directions. This difference in energy is emitted when the atom goes from one state to the other and has a wavelength of 21cm (or a frequency of 1420 MHz).

Since the emission comes from the hydrogen atoms in the plane of the galaxy, the velocity of the line with respect to the solar neighborhood (or the local standard of rest) can be used to study the structure of the galaxy and its rotation. A map of the galaxy in the emission of the HI line made with the Haystack small radio telescope is shown in Figure 7.

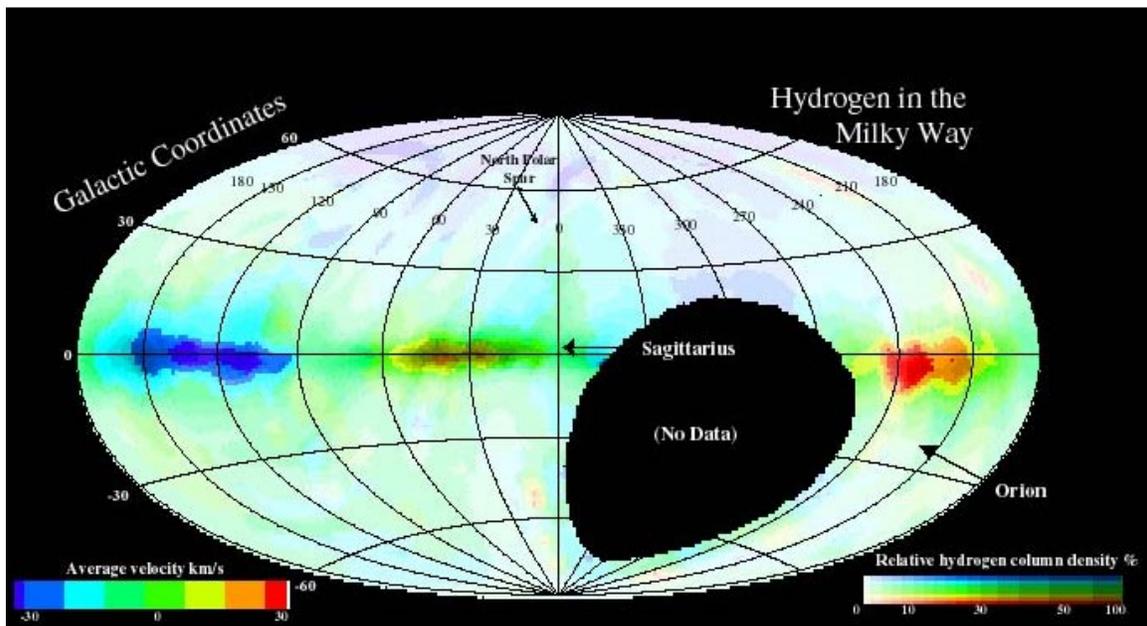


Figure 7

8.5 Extragalactic

One of the most striking discoveries of radio astronomy has been the spectacular jets from active galaxies. These jets have structures that are extremely complex. Jets from the galaxies have been imaged with extremely high resolution using Very Long Baseline Interferometric techniques. These images show that the jets are highly collimated very close to their origin. One famous example of such a jet is the source Cygnus A. Figure 8 shows an image of this source made with the Haystack 37-m telescope at a

frequency of 43 GHz. The image does not show much detail of the jet because the resolution of the system at this frequency is about 45". However, the two lobes of the jet are clearly seen. Note that the jets are much brighter than the galaxy from which they originate, which is situated at the center of the image.

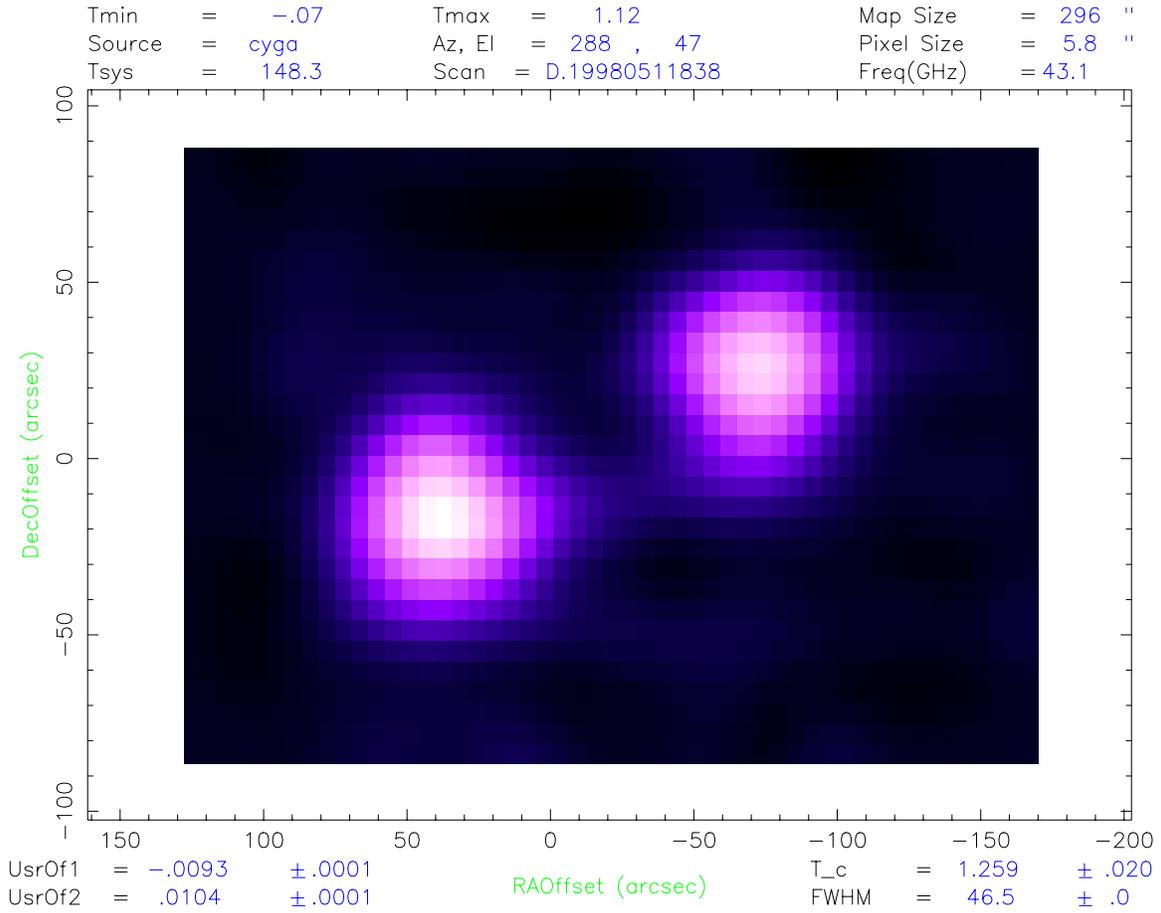


Figure 8