Progress in the research on cosmic rays has been deeply connected with that of radioastronomy, since the discovery of radio point sources in the late 1940's. In fact, the results from radioastronomical observations are, even now, playing an important role in the search for the structure of our Galaxy, in which most of the life of cosmic rays is spent. At present, the knowledge gained from radio observations covers many fields, such as the distributions of hot plasma gases, the structure of the galactic magnetic field, the distribution of high-energy electrons and of neutral hydrogen in the interstellar space and the activity of the galactic active nuclei.

Furthermore, as regards the problems related to the origin and the propagation of galactic cosmic rays, and supernovae and neutron stars as the possible sources of cosmic rays, for instance, the contributions of radio astronomy through the radio observations of supernova remnants such as the Crab nebula and various pulsars are extremely valuable.

5.1 Our Galaxy

The main constituents of the Galaxy are stars, interstellar gas and dust. Ionized plasmas and neutral atoms and molecules are also contained within the interstellar gases. In the interstellar space, there exist plasmas which are of extremely low density, but some are concentrated to make dense clouds here and there in this space.

The structure of the Galaxy is schematically indicated in Fig. 5.1.1. There remain many unsolved questions on the nucleus at the galactic center. Surrounding this nucleus, the Galaxy is formed like a huge disk. Our solar system is located in this disk. The mass density in the galactic disk tends to increase towards the galactic center. Like the Andromeda nebula and others, several arms spiralling outward from the galactic nucleus are known from radio astronomical observations. In fact, most of the neutral hydrogen and the galactic magnetic field are distributed along these spiral arms.

Many of the globular clusters are distributed spherically with respect to the galactic center as shown in Fig. 5.1.1. These clusters consist of about $10^3$–$10^6$ old stars which are now classified as the population II. At present, the distribution of these clusters in the Galaxy is thought to show the original shape of the primordial galaxy in
the early stage of its evolution. It seems that the globular clusters were formed as the stars of the first generation within such a galaxy. At the present moment, though being still controversial, there is an idea that the primordial gases which did not form these clusters still remain in a spherical shape, which is identified as the galactic halo.

5.2 Radio Observations

5.2.1 Radio telescopes

The general principle of the radio telescope is shown in Fig. 5.2.1. The energy of radio waves arriving from outer space is first picked up and then sent to the superheterodyne receiver. Defining the intermediate frequency of this receiver, the band width of the IF amplifier, and the integration time of the output with $f_i$, $\Delta f_i$, and $\tau$,
respectively, the fluctuation of the receiver output is statistically of the order given by

\[
\text{fluctuation/output} \approx \frac{1}{\sqrt{\Delta f \cdot \tau}},
\]

(5.2.1)
since the ratio proportional to the quantity \(\Delta f \cdot \tau\) consists of noise only. The output consists of the internal noise from the receiver system and of the cosmic radio waves collected by the antennas, but, since the latter intensity is extremely low, in order to catch these waves effectively, it is necessary to adjust both \(\Delta f\) and \(\tau\) to be as big as possible and to make the internal noise as low as we can.

When a black-body shutter which absorbs radio waves in the frequencies of 50–100 Hz is equipped with a waveguide or coaxial cable connecting the antennas with the receiver system, black-body radiation corresponding to room temperature reaches this system periodically. By means of this technique devised by Dicke,\textsuperscript{1)} the incoming radio waves are directly compared with the standard waves (the radio component of the black-body radiation from the shutter) and, as a result, a radio receiver whose sensitivity is close to the highest limit in principle can be manufactured.

The antennas are dealt with by replacing them with the equivalent resistances of temperature \(T\) in the electric circuit system. In the ideal case that there is no internal noise in the receiver system, their noise power \(P_0\) in the frequency range between \(f\) and \((f+df)\) is given by

\[
P_0 = kT \cdot \Delta f.
\]

(5.2.2)

When we take the noise power generated inside the receiver system and the incoming power as \(P_i\) and \(P\), respectively, the ratio \(N\), of the signal to noise ratio at the input side to that at the output side of the receiver is expressed as

\[
N = \frac{P_i/P_0}{P/(P_0 + P_i)} = \frac{P_0 + P_i}{P_0}.
\]

(5.2.3)

This ratio \(N\), being called the noise factor, makes it possible to estimate the order of the noise power generated inside the receiver. If this ratio is equal to 1 (i.e., \(N=1\)), it follows that the noise of the receiver system only consists of the antenna noise \(P_0\), which cannot be escaped in practice. This means that there is no noise source to cause any problem in the radio observations. In the case of a high-quality receiver system, it is possible to make \(N\) almost equal to 1 in the meter wave region. In the region from centimetric to decimetric frequencies, however, the range of \(N\) is from 3 to 10. In order for the incoming noise to be detectable, this noise must be more powerful compared to the fluctuation of the internal noise, and thus the following condition has to be satisfied:

\[
P \Delta f > (P_0 + P_i)/\sqrt{\Delta f \cdot \tau} = NkT \Delta f'/\sqrt{\Delta f' \cdot \tau}.
\]

(5.2.4)

The energy flux of radio waves incoming from the direction expressed by the
spherical coordinate \((\theta, \varphi)\), between \(f\) and \((f+df)\) inside the solid angle \(d\Omega\), is given by \(I_r(\theta, \varphi) df d\Omega\). If the radio energy to be transferred to the receiver from the antennas is taken as

\[
A(\theta, \varphi) I_r(\theta, \varphi) df d\Omega,
\]

the factor \(A(\theta, \varphi)\) is identified as the function to express the directivity of the antennas. Although an antenna is usually designed to be highly sensitive in its frontal direction \((\theta=0, \varphi=0)\), it is also more or less sensitive in other directions. The directivity of antennas is often expressed either by the effective solid angle as

\[
\Omega_0 = \frac{\int A(\theta, \varphi) d\Omega}{A(0, 0)}
\]

or, by the antenna gain as

\[
G = \frac{4\pi}{\Omega_0} = \frac{4\pi A(0, 0)}{\int A(\theta, \varphi) d\Omega}.
\]

Let us now try a thought-experiment on the transfer of radio energy in the frequency range \((f, f+df)\) between this receiver system and a black-body at far distance. We first assume the black-body at temperature \(T\), with a small solid angle \(\omega\), in the direction \((\theta, \varphi)\), and then that the antenna is well matched with the receiver system so that the power put into the antenna is totally absorbed and never reflected. This means that the end of the antenna is identified as the black-body. Since the antenna can, therefore, exchange the thermal radiation with the black-body in the direction \((\theta, \varphi)\), the temperature of the resistor at the end of the antenna becomes equal to \(T\) in the ideal case. Thus, the incoming energy from the black-body to the antenna is given by

\[
\frac{1}{2} \left( \frac{2kT \Delta f}{\lambda^2} \right) \cdot A(\theta, \varphi) \cdot \omega,
\]

where the factor \(1/2\) in this equation appears because the receiver system is only effective to the polarized component of the electric field in a definite direction. Furthermore, the formula of Rayleigh-Jeans is considered in the above equation as that of the black-body radiation with the assumption that \(hf \ll kT\).

In the thermal radiation emitted from the resistors at the end of the antenna, the electromagnetic energy to be absorbed by the black-body in the direction \((\theta, \varphi)\) is given as

\[
kT \Delta f \frac{A(\theta, \varphi)}{\int A(\theta, \varphi) d\Omega} \cdot \omega,
\]
since the directivity of the antenna is the same for both the incoming and the radiating fluxes because of the reciprocal principle in the electromagnetic theory. From Eqs. (5.2.7) and (5.2.9), it follows that

\[ \int A(\theta, \phi) d\Omega = \lambda^2 \]  \hspace{2cm} (5.2.10)

and

\[ A(0, 0) = G \frac{\lambda^2}{4\pi} . \]  \hspace{2cm} (5.2.11)

As being understood from the above treatment, the intensity of the cosmic radio emissions is often expressed by the term "temperature". In the case that the radio intensity in the frequency range \((f, f + df)\) is given by \(I_f df\), using the formula of Rayleigh-Jeans, the "brightness" temperature is defined as

\[ T_b = \frac{I_f \lambda^2}{2k} . \]  \hspace{2cm} (5.2.12)

The intensity \(I_f\) is measured in units of \(\text{W/m}^2\cdot\text{Hz}\), for instance. As shown by Eq. (5.2.12), the black-body temperature corresponds to the radio intensity given by \(I_f\). Practically, this temperature \(T_b\) is also used for the cases where the radio source is not necessarily identified as a black-body and that radio waves are emitted from some mechanism different from thermal processes. As considered in the thought-experiment mentioned earlier, the main reason that this temperature is often used is due to the fact that the function of radio telescopes can be easily understood from the thermodynamical point of view.

The antenna temperature \(T_a\) is defined as

\[ kT_a df = \frac{1}{2} \int \int A(\theta, \phi) \cdot I_f(\theta, \phi) d\Omega df. \]  \hspace{2cm} (5.2.13)

The right-hand side gives the total energy absorbed by the antenna in the frequency range \((f, f + df)\), while the left-hand side denotes the noise power generated when the temperature of the resistor at the end of the antenna is \(T_a\).

In the case in which the area covering the radio source is so wide that \(T_b\) is constant over a solid angle larger than \(\Omega_0\), it follows that \(T_a = T_b\). When the solid angle \(\Omega\) of the radio source is smaller than \(\Omega_0\), it becomes that \(T_a = T_b\Omega/\Omega_0\). In the case where \(\Omega < \Omega_0\), in particular, the results of the radio observations are often expressed by \(T_a\).

There are many large radio telescopes in the world. As the representatives of the completely steerable type antennas, the parabolic-dish radio telescopes are located in Bonn, West-Germany (200 m-diameter), Jodrell Bank, England (76 m-diameter), Parkes, Australia (64 m-diameter), and in Greenbank, U.S.A. (100 m-diameter). In
the mm wave frequencies, the sensitivity and the angular resolution of the 45 m-
diameter parabolic-disk radio telescope at the Nobeyama Radioastronomy Observa-
tory, University of Tokyo, are both the highest in the world at the present moment. The fixed 300 m-diameter spherical reflector radio telescope is located in Arecibo, Puerto Rico. This fixed antenna is able to observe celestial objects when they cross above it in the sky due to the earth’s rotation.

5.2.2 Radio interferometers

When superposed, radio waves, from a point source received at two antennas separated by the distance \( d \), interfere with each other and then generate the interferometer pattern. When this source moves across the front of the antennas, this pattern reaches the maximum in the angular direction \( \theta \) as determined by

\[
\frac{d}{\lambda} \sin \theta = n. \quad (n = 0, 1, 2, \ldots)
\] (5.2.14)

Thus, it follows that the width of interference fringes becomes smaller as this distance \( d \) increases. In the case where the radio source is extended in space, the shapes of these fringes become different from the case for a point source. For this reason, by synthesizing the interference fringes obtained by varying \( d \), on the contrary, it becomes possible to estimate the size and the shape of such extended radio sources. As derived from Eq. (5.2.14), for instance, it is possible to attain a resolving power of the order of 1 arc minute if the distance \( d \) is taken as several km for a wavelength of 1 m. By making an array of many full cross antennas instead of varying the distance \( d \), a sharp pencil-beam directivity is also attained.

This method, called aperture synthesis, has been applied to many radio telescopes such as those located at Cambridge, England (8 13 m-diameter parabolic-dish), Westerbork, the Netherlands (14 25 m-diameter dish) and Owens Valley, U.S.A. (27 25 m-diameter dish), for instances. At the Nobeyama Radioastronomy Observatory, 5 10 m-diameter parabolic-dish antennae can be used for radioastronomical observations. These dish can be moved a distance of about 600 m in two different directions and are designed to make the aperture synthesis of the records from these dishes.

If the intensity and the phase of the received radio waves can both be recorded exactly by each antenna, the distance \( d \) between two adjacent antennae can be made infinitely large in principle. In fact, if the phases of the local oscillators in different superheterodyne receivers can be correctly adjusted based on the frequency standard determined exactly by atomic clocks, it becomes possible to synthesize the records obtained from different receivers located at different sites. By means of this technique, called VLBI (Very Long Baseline Interferometry), the distance \( d \) can be extended to cover the whole earth by connecting two or more continents together. For instance, the distance of 7719 km between Hatcreek, California and Onsala, Sweden corresponds to \( 43 \times 10^3 \) 18 m-diameter parabolic-dishes, and the resolving power reaches 0.0015 minutes of arc. The radio telescope at the Nobeyama Radioastronomy
Observatory is also now being planned to be used as one of these interferometers. As a result, the resolving power in radioastronomical observations is now higher than those in the optical and the X-ray observations, whose resolving powers are several minutes of arc at most. As examples of observations with such high resolving power, the structure at the center of the quasar 3C 273, the jet seen at the center of radio galaxy NGC 6251 and the structure of the OH radio source in hot nebulae have already been made clear in detail.

5.2.3 The sky as seen by radio waves

Up to now, using many radio telescopes and interferometers, the survey of the celestial sphere has been made to obtain the radio brightness distribution at different frequencies. The two radio maps of this distribution at 150 and 408 MHz are respectively shown in Fig. 5.2.2 as examples of this survey. In this figure, the equi-$T_b$ curves are drawn on the charts as being referred to the galactic coordinate system. When looking at these maps, several important features are noticed:

1) The galactic disk is generally bright.
2) The galactic center is remarkably brighter.
3) The radio brightness is not uniformly distributed in the high latitude regions. In particular, the most significant is the structure extending northward from the disk at about 30° galactic longitude. This structure is now known as the north-polar spur, which seems to extend circularly over the celestial sphere. This was already noticed on the radio map at 200 MHz obtained in the 1950's, and, since then, many ideas have been proposed to explain the cause of this structure. At present, it is thought to be the trace of a shock wave generated in the region not far from the solar system in ancient times.

Many structures similar to the feature of this north-polar spur have now been found. The radio map shown in Fig. 5.2.2(b) suggests that, though their scales are not so large, many such traces similar to the north-polar spur have been formed in the galactic space.

4) Along the galactic disk, brightened regions are seen here and there. These regions are clearly seen in the higher frequency regions. The radio maps along the galactic disk observed at 820 MHz and 4170 MHz are, respectively, shown in Figs. 5.2.3(a) and (b). Several compact radio sources are clearly seen on these maps.

5.2.4 Non-thermal and thermal radio emissions

The radio waves being emitted from celestial objects by non-thermal processes are mostly identified as those from the synchrotron mechanism, as has been considered in Chapter 3. In the case where the ensemble of electrons in motion is expressed by the differential energy spectrum $E^{-\gamma}$, the frequency spectrum of the emissivity from the synchrotron radiation by these electrons spiralling in a magnetic field is given by $f^{-(\gamma-1)/2} df$.

Thermal radiation is, of course, the black-body one if celestial objects are always black-bodies. In the case where these objects are semi-transparent, the frequency spectrum of this radiation is schematically given as shown in Fig. 5.2.4. The thermal
Fig. 5.2.2. The celestial spherical distribution on the radio emission intensity (the representation by the galactic coordinate system) (a) 150 MHz (Landocker and Wielebink), (b) 408 MHz (Haslam et al.).
Fig. 5.2.3. The galactic plane as viewed from the radio emissions (a) 820 MHz\textsuperscript{13}, (b) 4170 MHz (Radio Research Lab., Kashima).
radiation like this is denoted as either the free-free emission or thermal bremsstrahlung. The feature of this spectrum is that the intensity is nearly constant in the frequency range of $hf < kT$, but becomes exponential in the frequency range $hf \geq kT$. Since the absorption of radio waves becomes strong in the extremely low-frequency region, the thermal radiation becomes that of a black-body and thus its spectrum is expressed by the formula of Rayleigh-Jeans, which is proportional to $f^2$, as well known.

The observed results on the brightness temperature $T_b$ or the radio intensity $I_r$ per unit frequency, with respect to the direction separated from the galactic plane by several degrees or more, are summarized as

$$T_b \propto f^{-2.5 \sim -2.7} \quad \text{and} \quad I_r \propto f^{-0.5 \sim 0.7} \quad \text{for } f \ll 3000 \text{ MHz}$$

and

$$T_b \propto f^{-2.0} \quad \text{and} \quad I_r \approx \text{constant for } f > 3000 \text{ MHz}.$$ 

These results can be well explained by assuming that, in the frequency region less than 3000 MHz, radio waves are emitted from electrons with the energy spectrum $E^{-\gamma}$ ($\gamma = 2.0 \sim 2.4$) by the synchrotron mechanism, while thermal radiation from semi-transparent hot gases is responsible in the frequency range higher than 3000 MHz.

The north-polar spur, seen in the high galactic latitude region, is often called the Loop I from its circular pattern. Various structures such as Loop II and others are also seen in Fig. 5.2.2(b). The radio waves from Loop I seem to be emitted by the synchrotron mechanism from high-energy electrons as viewed from their frequency spectral shape and polarization.

From the sky survey of soft X-ray emissions as done by the Nagoya-Leiden and the Wisconsin groups, it has been found that there exist high-temperature plasmas of $10^6 \text{ K}$ or more inside the Loop I structure. The observations by the large X-ray astronomy satellite HEAO-1, furthermore, suggest that the structures as seen in the
high galactic latitude region may be identified as shock waves generated from supernova explosions and that one-third or more of the interstellar space have now been covered by high-temperature plasma cavities swept up by the shock waves.

In the regions at galactic latitudes higher than 4°, the brightness temperature $T_b$ tends to increase almost in proportion to $\lambda^{2.6}$, where $\lambda$ is the radio wave length, while it is seen that, in the low latitude region along the galactic plane, the radio intensity decreases in the wavelength region longer than $4\sim5$ m. The cause of such a change may be explained by taking into account the extensive absorption of synchrotron emissions by plasmas extending along the galactic plane. In the short wavelength region, the galactic disk with thickness about 2° is very clearly seen along the galactic plane as shown in Fig. 5.2.3(b). In this disk region, there are many hot plasma clouds, called the H II clouds, which are highly brightened, but, apart from these clouds, non-thermal radiation can be also observed in the frequencies between $1000\sim3000$ MHz in the galactic disk. This result seems to indicate that hot plasmas are ambient uniformly in this disk, in addition to hot plasma clouds.

Many observed results on the background synchrotron radiation in the Galaxy are summarized in Fig. 5.2.5, in which the spectra in the low frequency side are extrapolated by referring to the shapes of the spectra in the higher frequency range. In this figure, the results at frequencies less than 3 MHz have been obtained by satellite observations. The spectral shape is expressed as $f^{-0.5\sim0.7}$ at frequencies higher than 100 MHz, while the absorption by the hot plasma electrons in interstellar space becomes significant in the regions along the galactic plane, in particular, near the galactic center. It is thought that, at radio frequencies less than 1 MHz, the interstellar space within several 100 pc distant from us can only be seen through because of strong absorption of radio waves. In particular, strong absorption is clearly seen in the direction to the anti-center of the Galaxy, since the solar system is located inside one of the galactic arms. In the background radiation in the frequency region higher than

![Radio Intensity vs. Wave Frequency](image)

**Fig. 5.2.5.** The frequency spectra on the galactic radio emissions.
1000 MHz, the frequency spectrum interpretable at the 3 K black-body radiation is certainly found as shown in Fig. 5.2.5.

5.3 The Structure of Our Galaxy

5.3.1 The observations of pulsars—Plasmas and magnetic fields in interstellar space

The first pulsar was accidentally discovered in late 1967 by using the radio interferometers at 81.5 MHz at the University of Cambridge. This was observed as a pulsating radio phenomenon with a period which remained almost constant for several months. The fluctuation of this period was of the order of $10^{-7}$, and its pulsating period was identified as about equal to 1 second. Based on these results, being irrespective of the emission mechanism of its radio waves, it was soon thought that this celestial object must be a new object identified as a rapidly rotating neutron star. This idea of pulsars is well accepted in the astronomy community at present.

The neutron star had been predicted as one of the superdense stars by Oppenheimer and others, using the theory of general relativity, soon after the discovery of the neutron by Chadwick. In 1934, Baade and Zwicky also predicted that the neutron stars might have been produced in association with supernova explosions. Many years later, a pulsar was actually discovered in the Crab nebula, a typical supernova remnant, as predicted by theoretical studies. In accordance with the prediction made by Gold, who proposed the neutron star model of pulsars, it was discovered that the pulsating period of the Crab pulsar is now becoming longer at the rate of $4.2 \times 10^{-13}$ sec per second, since, as predicted by him, the rotating period of a neutron star has to become longer as a result of the loss of its energy by radio emissions. As has later been measured exactly by X-ray observations, the mass ($M$) and the radius ($R$) of a typical neutron star are, respectively, given by

$$M \approx 1.4 \, M_{\odot} \quad (M_{\odot}: \text{Solar mass})$$

and

$$R \approx 10 \, \text{km}.$$ 

The number of pulsars discovered up to now is about 200, and most of them are located in the region of galactic latitude less than several degrees from the galactic plane. By taking into account that the group velocity of radio waves is determined by both the wave frequency and the plasma density in their propagation in a plasma medium, it is possible to estimate the column density of electrons along the path of radio waves in this medium.

This group velocity is expressed as

$$v_g = c(1 - \frac{\omega_p^2}{\omega^2})^{1/2},$$

where $\omega$ is the angular wave frequency and $\omega_p^2 = (4\pi ne^2/m)^{1/2}$ defines the plasma
frequency.

The difference between the arrival times of the pulses at two different frequencies is calculated as follows:

\[ t_2 - t_1 = \frac{2\pi e^2}{mc} (\omega_2^{-2} - \omega_1^{-2}) \int n_e dl, \tag{5.3.1} \]

where \( \int n_e dl \) is the column density of electrons along the path of these radio waves. Using the relation \( f = \omega / 2\pi \), the dispersion measure (DM) is defined as

\[ \text{DM} = \frac{2\pi mc}{e^2} \cdot D \]

where \( D \) is defined by \( D = (t_2 - t_1) / (f_2^{-2} - f_1^{-2}) \). Substituting numerical values into this equation, it follows that

\[ \text{DM (cm}^{-3} \cdot \text{pc}) = 2.4 \times 10^{-16} D \text{ (Hz)}. \tag{5.3.2} \]

From the above definition, it follows that DM is related to the mean electron density and the distance \( d \) to the pulsar by

\[ \langle n_e \rangle = \frac{\text{DM}}{d}. \tag{5.3.3} \]

Since it is known that the magnitude of DM is significantly large at galactic latitudes less than several degrees, it is clear that the plasma density is comparatively higher along the galactic plane.

Using the estimated results on the hydrogen density in interstellar space based on the observed data of the interstellar absorption of 21 cm radio emissions, which will be considered later, it becomes possible to estimate the distance \( d \) to radio sources under study. Up to now, these distances have been estimated for about 30 pulsars by means of this procedure. The electron density in the interstellar space as estimated from both DM and the distance \( d \) is 0.03/cm\(^3\).

When an electromagnetic wave propagates in a direction making angle \( \theta \) with the magnetic vector in a magnetoactive plasma, its polarization vector circularly rotates in the right handed way. This is the phenomenon called the Faraday rotation. The rotating angle of this vector is expressed as

\[ x = RM \cdot \lambda^2, \]

where

\[ RM = \frac{e^3}{2\pi m^2 c^4} \int n_e B \cos \theta dl. \tag{5.3.4} \]
In this equation, the term $B \cos \theta$ represents the component of the magnetic field along the direction of the radio wave propagation. This angle is proportional to the plasma density and $B$ and the square of the radio wavelength. Since the magnetic intensity can be connected with $RM/DM$ using Eq. (5.3.4), the mean intensity of the galactic magnetic field can be calculated as

$$\langle B \cos \theta \rangle = \frac{\int n_e B \cos \theta \, dl}{\int n_e \, dl} = \frac{1.23 \, Z \, R \, M}{DM} \quad (\mu\text{gauss-rad}\cdot\text{m}^{-2}) \quad (5.3.5)$$

It thus follows that this intensity is of the order of $1 \mu$ gauss ($10^{-6}$ gauss). Since the directions of the galactic magnetic fields are distributed as shown in Fig. 5.3.1, it is possible to draw a picture of the large-scale structure of these fields in the interstellar space.

5.3.2 **Cosmic dust in the galactic magnetic fields**

Generally speaking, the lights from the distant stars are usually polarized. The colors of these stars change with their spectral types that are dependent on their surface temperature. Also, their colors are reddened in most cases as compared with the colors expected from their spectral types. Furthermore, it has been known that the degrees of the reddening of the star lights are correlated to those of the polarization of the lights from the same stars.

It seems that both the reddening and the polarization of the star lights are induced due to the action of the dust particles in the interstellar space. These dust particles seem to be rotating like small tops, since their shape may be flattened or elongated. If these particles consist of paramagnetic substances and are located in a

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**Fig. 5.3.1.** The interstellar magnetic field (Manchester et al.).
magnetic field, they necessarily make a kind of precession motion around the field lines like tops because of the magnetic force on them. In consequence, these dust particles would become aligned along the magnetic field as if they were a chain of small beads or buttons. In any case, the short axes of these particles are well aligned along the magnetic field.

So far, many theoretical treatments have been done on the scattering of light by the particles of flattened dusts, whose axial directions are aligned. If the size of the dust particles is of the order of the optical wavelength on average, the polarized electric vectors of the star lights perpendicular to the direction of the magnetic field, namely, along the direction of the longer axes of these particles, are either efficiently scattered or absorbed by these particles. Whereas, the electric vectors of these lights in the direction of the magnetic field are mostly able to propagate through the space without being much disturbed. This is the reason why the observed star lights are to some extent polarized.

Figure 5.3.2 shows both the direction and the magnitude of the polarization of star lights plotted as a function of the galactic coordinate system. The direction of this polarization shows a wavy structure in some direction from the solar system. This suggests that the magnetic field in the interstellar space is distributed in a wide region with kind of regular structure. Since the star lights are most effectively polarized in the interstellar region within about 1000 light years of the solar system, this result further suggests that, in the region relatively close to us, the magnetic field is to some extent distributed uniformly into some specific direction. As shown in Fig. 5.3.2, the observed data on the polarization of the star lights bring to us the structure of the magnetic field perpendicular to the line of sight in the galactic space, whereas the observations on the Faraday rotation give the information to the distribution of the magnetic field along the line of sight. By synthesizing these two observations together, the three-dimensional structure of the galactic magnetic field can be necessarily made clear.

5.3.3 21-cm radio emissions

The hyper-fine structure in the energy levels of atomic hydrogen is given as

\[
W = \frac{hf_0}{n^3} \left[ \frac{F(F+1) - (I+1) - (J+1)}{J(J+1)(2L+1)} \right],
\]

where \( n, I, L \) and \( S \) are, respectively, the principal quantum number, the proton spin, the orbital angular momentum and the electron spin and \( F=J+I \), and \( J=L+S \). Furthermore, \( f_0 = g\alpha^2 c R \), where \( g \) is the Landé factor of the proton and \( R \) is the Rydberg constant given by \( \approx 532.65 \) MHz. At the lowest energy level, these quantities are given as \( L=0, S=1/2, J=1/2, I=1/2 \) and \( F=1 \) or \( 0 \). Corresponding to the states \( F=1 \) and \( 0 \), namely, the transition between the parallel and the anti-parallel states as regards both the spins of the proton and electron, electromagnetic waves of \( f=1420.4058 \pm 0.0003 \) MHz are radiated or absorbed. These waves are the so-called 21-cm waves.
Fig. 5.3.2. The magnetic field vector distributions as deduced from the polarization of the star light (after Heiles).
In the interstellar gas clouds containing a number of hydrogens, hydrogen atoms corresponding to those two states as mentioned above are distributed in some proportion as determined by the temperature and the gas density of these clouds. The existence and the observability of these waves in the interstellar space was first predicted by van de Hulst\(^7\) in 1944 and their existence was eventually discovered by the radio astronomy groups in U.S. and Australia in 1951. The progress of the radio astronomical research on the interstellar medium has accelerated since the discovery of these 21-cm waves, and the distribution and the large-scale motion of the interstellar hydrogens have been successfully made clear through the systematic observations of these waves.

As mentioned above, if this line emission can be detected, it is possible to examine the density distribution of the neutral hydrogen gases in the interstellar space on the basis of the observed results on the global distribution of the 21-cm waves in the celestial sphere. Furthermore, by measuring the absorption profile of the 21-cm waves in the radio frequency spectra of some radio sources, it becomes possible to study the distribution of hydrogen gases between these sources and us. The velocity profile of these gases along the line of sight can also be examined from the measurement of the Doppler effect observed on these waves. If the broadening in the emission spectra of the 21-cm waves can be found, the temperature and the turbulent motion of hot hydrogen gases can be estimated together.

In the 1960s, based on the observed results on these wave emissions, the picture of the interstellar structure had been drawn as follows: the gas clouds consisting of neutral hydrogens, the so-called HI clouds, are distributed in various corners in the interstellar space and the young stars are born in these clouds. These clouds are usually surrounded by hotter plasmas. The density and the temperature of hydrogen in the HI clouds are of the order of \(1/cm^3\) and 100 K, respectively, while the density and the temperature of plasmas in the hot plasma clouds, the so-called HII regions, are respectively of the order of \(0.01/cm^3\) and \(10^4\) K. Thus the equilibrium condition is well satisfied between these two clouds.

On the contrary, the map of the large-scale distribution of the interstellar hydrogen as obtained by Heiles and others\(^8\) from the sky survey by the 21-cm waves appears much different from the picture as mentioned above. In fact, according to their results, the shape of the HI clouds is not round like a sphere, but shows filamentary structures elongated as cigars, whose size is typically 100 pc in length and 10 pc in width. The directions of these filaments are mostly coincident with the polarization planes of the star lights and so seem to be parallel to the interstellar magnetic field. These filamentary structures may be explicable as the regions called the hot bubbles produced from the supernova remnants in the interstellar space. The features which had once been identified as the HI clouds may have been the cross-sectional structure of these filaments. It is certain that static equilibrium is never established in the interstellar space since shock waves from many supernova remnants are always violently interacting to produce hot plasma regions (see Chapter 6).

The other important result from the observations of 21-cm waves is related to the large-scale motion of the masses of neutral hydrogen in the Galaxy. Figure 5.3.3
shows the dynamic spectra of the moving velocity of hydrogen atoms in the line of sight as calculated from the observed Doppler shifts of 21-cm waves in the galactic plane with respect to galactic longitude. In this figure, three peaks corresponding to the clusterings of hydrogen gases are seen in most longitude zones. From the differences of the Doppler shifts, it follows that these clusterings move with different velocities. Though the shape of the dynamic spectra gradually changes with the galactic longitude \( l \), Figure 5.3.3 clearly shows that some clusterings of these gases are often extended over the longitude region wider than 90°. In other cases, clusterings are newly formed in a specific longitude zone. These observed results indicate that these clusterings of hydrogen gases are connected with each other like a long chain. Thus, these clusterings are identified as a part of the spiral structure of our Galaxy, which we view from earth.

Let us now assume that those hydrogen gases are circularly rotating around the center of the Galaxy and that the angular velocity of this rotation is a function of the distance from this center. In this case, the velocity \( \nu \) of hydrogen gases in the line of sight as estimated from the Doppler effect on these gases is generally expressed as

\[
\nu = R_0(\omega(R) - \omega_0) \sin l,
\]

where \( R_0, \omega_0 \) and \( \omega(R) \) are, respectively, the distance from the galactic center to the solar system, the angular velocity of the solar system with respect to the galactic center and the angular velocity at the radius \( R \). By solving the above equation by reference to
the observed values of $v$ for several different values of the galactic longitude $l$, the structure of the spiral arms is determined theoretically.

5.3.4 The spiral structure of our Galaxy

That many of the galaxies have spiral structure is well known from the observations of the Andromeda nebula, the galaxy M51 in the constellation Canis Venaciti and other galaxies. Our Galaxy also has a similar structure to these galaxies.

Generally speaking, the absolute magnitudes of the stars are uniquely determined by their spectral types. Therefore, among the stars of the same spectral type, the bright ones are close to the solar system, while the dark ones are far from us. When the distances of many of the nearby stars from us are measured by referring to this criterion, it follows that most of these stars are distribute in a belt, which forms a part of the spiral structure of the Galaxy. The analysis of the observed data on the 21-cm wave emissions has revealed the spiral structure of the Galaxy in the distribution of neutral hydrogens. Figure 5.3.4 shows the distribution of these hydrogens in the galactic plane, which had been obtained by Oort.\(^9\) In this figure, however, there remain some ambiguities in the hydrogen distribution, since the motion of hydrogen gases is not perfectly concentric and the Galaxy has some local irregular structures in many different locations. Although some spiral arms are connected with each other in an unnatural way as shown in this figure, this is an important result well known historically, and even now cited by many researchers.

![Diagram of the spiral structure of the Galaxy](image)

Fig. 5.3.4. The distribution of neutral hydrogens in the galactic plane as referred to the galactic longitude (Oort).
The $l$-$v$ diagram deduced from the 21-cm wave observations for the region near the galactic center is schematically indicated in Fig. 5.3.5. Since both A and A' are located at the regions of about 4 kpc far away from the galactic center, they are often called the 4 kpc arms. If these arms were circularly rotating around the galactic center, A would be an oblique line across the center in this diagram. The discrepancy as seen in Fig. 5.3.5 might have been, however, attributed to the expanding motion of this arm with its rotation around the galactic center. Furthermore, this figure indicates some violent gas motions in the direction $l=0^\circ$, since the 21-cm line emissions are widely Doppler-shifted. In addition, the two wings, B and B' seem to be superposed on these motions. This result suggests that expanding gases with rapid rotation are distributed in the area toward the direction of the galactic center. So to speak, the galactic center appears as if it is ejecting gases violently while rapidly rotating.

It seems that some violent phenomena have been occurring at the central part of our Galaxy, though their nature is hidden from us. In fact, some activities have also been found in the Andromeda nebula like our Galaxy. Furthermore, it is known that some galaxies such as Seyfert galaxies, Virgo-A (M87), M82 or the quasars are exploding in their central parts and releasing an enormous amount of energy outward.

The amount of energy being released from the central core of our Galaxy can be estimated from the observations of the 21-cm wave emissions around the galactic center. This energy output reaches about $4 \times 10^{40}$ erg/sec within the region of 1 pc in diameter. Referring to the typical energy output in the life of a star to be about $10^{44}$ erg, this output may be said to be large beyond our expectation. However, nothing has ever been understood as yet on the nature of this energy source.

Many discrete line emissions other than the 21-cm line emission have already been discovered in the radio frequencies; they are, for instance, emitted from the molecules such as OH, HCHO, NH$_3$, H$_2$O, HCN, CO, and many others. Most of these

![Fig. 5.3.5. The Doppler shift as seen on the motion of hydrogen gases in the galactic plane.](image)
emissions seem to be produced by the maser processes taking place in the interstellar molecular clouds. The wavelengths of the radiances from the radical OH are around 18 cm, and are determined from its transition processes. From the analysis on the Doppler shift of these wavelengths seen on the absorption spectra, it has become clear that, far inside of the 4 kpc arms, there exist large gas clouds which are falling down into the galactic center as rapidly rotating and that expanding structures with rotation are located about 1000 light years from the solar system.

According to the observations of the intensities of the non-thermal radio emissions at radio frequencies such as 85.5, 408 and 1440 MHz, this intensity seems to change step-wise with galactic longitude in the galactic plane.\(^{10}\) The cause of such step-wise changes in the radio intensity seems to be related to the magnetic structure associated with the spiral arms of the Galaxy. If high-energy electrons were distributed along these arms, these step-wise changes in the radio intensity would be formed respectively in association with the changes of the arms’ directions.

As has been described in the foregoing paragraphs, all of the distributions of the stars, neutral hydrogen gases, the interstellar magnetic field and associated high-energy electrons show the same pattern as the spiral or the concentric structures. At any rate, there exist more or less the arm structures in the galactic plane.

5.3.5 *Hot plasma regions*

A number of the radio sources in and near the galactic plane as shown in Fig. 5.1.2.3 are identified as thermal ones associated with high-temperature interstellar clouds. The large gas cloud seen in the constellation Orion may be considered as representative among them. An enormous amount of neutral and ionized gases are abundant in this cloud and the proto-stars and young stars just after birth are also found here and there inside the cloud. Furthermore, several molecular line emissions are observed which are being emitted from various sites of the cloud. It is now thought that these molecules are playing a role as the catalyst for the gases there to contract to become the proto-stars.

Furthermore, it seems that hot tenous plasmas other than gas clouds are ambient in the galactic plane, too. Thus, it seems that the interstellar space is occupied by these plasmas and the hot bubbles as detected from the soft X-ray observations. Such a dynamic image could be said to be completely different from that prevailing almost 10 years ago, which constituted neutral gas and plasma clouds.

5.4 *Cosmic Electrons*

5.4.1 *The energy spectra of cosmic electrons*

Among the cosmic electrons, the low-energy component is absorbed by the atmospheric constituents immediately after entering the earth’s upper atmosphere, while the high-energy component produce the cascade showers, consisting of the secondary electrons, neutrinos and photons, from the interaction with those constituents. These electrons are, therefore, not directly detected on the ground, because their secondary electrons are mixed up with the secondary components.
yielded by cosmic ray nuclei. For this reason, these electrons have to be primarily measured by means of balloons and satellites above the atmosphere. Because of this circumstance and of their low flux as compared to the incident flux of cosmic ray nuclei, the experimental observations on the cosmic electrons were only started in the 1960's. Recently, these electrons have been measured in a wide energy range by using mainly transition-meters, superconducting magnets, emulsion-chambers and others on board balloons. Most of the observed results are summarized in Fig. 4.3.4, in which the results on the high energy electrons up to 1000 GeV have been obtained by the Japanese groups led by Nishimura by using the emulsion chambers. Because of the sharp gradient of their spectrum, the energy spectrum of high-energy electrons multiplied with $E^3$ is indicated in Fig. 4.3.5.

Cosmic electrons are confined in the Galaxy due to the action of the galactic magnetic field in the same ways as cosmic ray nuclei, and are either directly observed when they arrive at the earth and its neighborhood, or indirectly detected from the observations of the synchrotron radiation from these electrons due to their interaction with the magnetic field in interstellar space. The questions related to the energy spectra of the cosmic electrons and the non-thermal spectra associated with the synchrotron radiation from these electrons are very much concerned with research on the structure of the galactic magnetic field and the distribution of the interstellar gases and the galactic confinement of cosmic rays. Up to now, these questions have only partly been understood, but there still remain many other questions associated with the origin and the propagation of cosmic rays as seen in the discussion in the other chapters of this book. In this context, we shall consider a plausible idea on the behavior of cosmic electrons.

The energy loss process of cosmic electrons in interstellar space will be generally expressed as

$$\frac{-dE}{dt} = a_1 n + a_2 n E + (a_3 B^2 + a_4) E^2,$$  \hspace{1cm} (5.4.1)

where $E$, $n$ and $B$ are the electron energy, the background gas density and the strength of the galactic magnetic field, respectively. Also, the factors $a_1$, $a_2$, $a_3$ and $a_4$ are the constant parameters for the energy losses. In the above equation, the first term on the right-hand side shows the energy loss due to the collision of the electrons with the background gases, while the second term shows the energy loss due to the bremsstrahlung by the collision of the electrons with interstellar nuclei, mainly protons. Among the two terms proportional to $E^2$, the first and the second are, respectively, due to the synchrotron radiation and the inverse-Compton radiation. In interstellar space, however, both the first and the fourth terms in Eq. (5.4.1) can usually be neglected. Denoting the differential energy spectrum of electrons at their source with $q(E) dE$ and assuming that, in addition to those energy losses given by Eq. (5.4.1), these electrons are leaked away from the Galaxy in the life given by $\tau$, the differential energy spectrum of these electrons in the steady state is expressed as
\[ \frac{d}{dE} \left[ -\frac{dE}{dt} N(E) \right] + \frac{N(E)}{\tau} = q(E). \]  

(5.4.2)

Although many different models have been proposed of the leakage of cosmic electrons from the Galaxy, it is assumed for simplicity that these electrons are lost together with cosmic ray nuclei in the same life time \(\tau\). At present, from the consideration of the chemical composition of cosmic rays as deduced from the model of their confinement in the galactic disk, it is thought that this life \(\tau\) for the nuclei is of the order of \(10^6 \sim 10^7\) years. On the other hand, the measured results of the relative abundance of \(^{10}\)Be nuclei in cosmic rays give this life \(\tau\) to be almost equal to \(1.6 \times 10^7\) years, consistent with the above value (see Section 4.3).

In the case where the life \(\tau\) is weakly dependent on the electron energy \(E\), as long as this life is not much different from that as given above (less than \(2 \times 10^5\) years), the bremsstrahlung can be neglected for electrons in comparison with their leakage from the Galaxy when the number density of the interstellar gases \(n\) is between 0.1 and \(1/\text{cm}^3\), as is usually considered. As a result, the following equation is reduced:

\[ \frac{d}{dE} \left( -a_3B^2E^2N(E) \right) + \frac{N(E)}{\tau} = q(E). \]  

(5.4.3)

When we assume the energy spectrum to follow a power law, the first term on the left-hand side can be neglected for the case for \(E \ll E_c = 1/\tau a_3B^2\), and the following equation is obtained:

\[ \frac{N(E)}{\tau} = q(E). \]  

(5.4.4)

Whereas, as regards the case for \(E \gg E_c\), the first term on the left-hand side becomes important. Thus, Eq. (5.4.3) is approximated as

\[ -a_3B^2 \frac{d}{dE} (E^2N(E)) = q(E), \]  

(5.4.5)

where \(a_3 = (2c/3)(e^4/(mc^2))^4\). When \(B\) and \(E\) are expressed in the units of gauss and erg, respectively, it follows that \(a_3 \approx 2.4 \times 10^{-3}\). If the form \(q(E) \propto E^{-m}\) is assumed, the energy spectra \(N(E)\) for the cases \(E \ll E_c\) and \(E \gg E_c\) become proportional to \(E^{-m}\) and \(E^{-(m+1)}\), respectively. In other words, the energy spectrum of cosmic electrons changes largely in accordance with the electron energy higher or lower than the critical energy \(E_c\). In fact, at energies higher than \(E_c\), electrons lose their energy mainly due to the synchrotron radiation as a result of their interaction with the galactic magnetic field.

Since the life \(\tau\) is dependent on the particle energy \(E\), in practice, the treatment of Eq. (5.4.2) is not so simple. For this reason, in general, the functional form of \(\tau\) is assumed as \(\tau = \tau_0(E/E_0)^{-3}\), and this expression is taken as common to both cosmic electrons and cosmic ray nuclei. In other words, it is assumed that the leak of these
particles from the Galaxy is only determined by their motion in the galactic magnetic field. Referring to the observed results that the ratio of the light to the medium nuclei in cosmic rays \((L/M)\) becomes smaller with particle energy, it follows that \(\tau\) must become shorter with \(E\) dependent on \(\delta=0.3\sim0.5\). It thus becomes possible to consider the model of the propagation of cosmic rays in the galactic space on the basis of detailed studies of the functional form of \(\tau\). From Fig. 4.3.5, it is evident that the power index of the energy spectrum for cosmic electrons is given as \(2.6\sim3.0\) around the 10 GeV-energy, but becomes \(3.0\sim3.5\) in the energy range higher than 1000 GeV.

### 5.4.2 Synchrotron emission processes

Let us briefly consider the characteristics of the synchrotron emissions from high-energy electrons (see Chapter 3 for the detail). The ensemble of these electrons moving in a magnetic field \(B\) with the differential energy spectrum given as

\[
N(E)\,dE = KE^{-\gamma}\,dE
\]  

(5.4.6)

radiates the energy from unit volume as determined by the frequency spectrum given by

\[
P(f) = \frac{\sqrt{3}K}{2} \left( \frac{e^3 B_\perp}{m c^2} \right) \left( \frac{3eB_\perp}{4\pi m^3 c^5} \right)^{(\gamma-1)/2} \frac{\omega(\gamma)}{f^{(\gamma-1)/2}},
\]  

(5.4.7)

where \(\omega(\gamma)\) is a constant nearly equal to 0.17 and \(B_\perp\) is the component of \(B\) perpendicular to the electron orbit. By substituting the numerical values for \(m, c\) and \(e\) into Eq. (5.4.7), \(P(f)\) is given as

\[
P(f) \approx 2.4 \times 10^{-24} \cdot K \cdot B_\perp^{(\gamma+1)/2} \left( \frac{6.26 \times 10^{18}}{f} \right)^{(\gamma-1)/2} \text{ W/m}^3 \cdot \text{Hz}. \quad (5.4.8)
\]

The frequency at the peak flux is estimated as

\[
f_m \approx 0.29 \times \frac{3}{4\pi} \frac{eB_\perp}{mc} \left( \frac{E}{mc^2} \right)^2
\]

\[
\approx 1.2 \times 10^6 B_\perp \left( \frac{E}{mc^2} \right)^2 \text{ Hz.} \quad (5.4.9)
\]

The index \((\gamma-1)/2\) is \(0.8\sim1\) for electrons of energy 10 GeV. In the case where the strength of the interstellar magnetic field is \(3\times10^{-6}\) gauss, the frequency \(v_m\) is estimated to be of the order of 1500 MHz. According to the radio astronomical observations on the galactic radio emissions at frequencies of \(10^2\sim10^4\) MHz, the index of the power law spectrum is \(0.8\sim0.95\). These values agree well with the power of \((\gamma-1)/2\) since \(\gamma\approx2.6\sim3\). However, the observed intensity of the radio emissions is too high to be explained by taking into account the theoretical intensity expected from the energy spectrum of electrons. As an interpretation of this discrepancy, some
modification may be considered either on the electron density in interstellar space as deduced from the observed results of electrons near the earth, or on the magnetic field intensity as estimated from radio and optical observations. Since the emissivity of synchrotron radiation is proportional to $B^2$, in the case where the galactic magnetic field is non-uniform and irregular, the mean value of $B^2$ always becomes larger than the square of the mean value of $B$. This may also play a part in the discrepancy mentioned above.

5.4.3 The halo—does it exist or not?

Non-thermal radio emissions are, in general, strong in the galactic plane, but these emissions also arrive from high galactic latitudes, though their flux is much less intense. Taking into account this result, Shklovsky put forward an idea that these weak emissions must have originated in some region far out of the galactic plane.\textsuperscript{11} Later, it became evident that, according to the radioastronomical observation by Baldwin, the radio intensity from the direction $l=0^\circ$ and $b=\pm45^\circ$ was about three times higher than that from the direction $l=180^\circ$ and $b=\pm45^\circ$, where $l$ and $b$ are the galactic longitude and latitude, respectively. Referring to these observed results, in 1955 he proposed a model in which high-energy electrons are confined in a spherical region, covering the Galaxy, in which plasmas co-exist with magnetic fields.\textsuperscript{12} This region, called the halo or the galactic corona, was considered to be identified as the source of non-thermal radio emissions from the high latitude region of the Galaxy. According to recent observations on other galaxies, it has been found in some cases that the extension of the radio bright region is larger than that of the optically bright region.

The arrival directions of cosmic rays at the solar system are almost uniformly distributed in the celestial sphere, and the anisotropy on these directions is less than $10^{-4}$ at a particle energy of $10^{12}$ eV. This observed result is easily understood if the motions of cosmic rays are well randomized by the magnetic field in the halo even if the cosmic ray sources are not uniformly distributed in the Galaxy.

There perhaps remained tenuous plasma gases in the primordial spherical galaxy sometime after the formation of globular clusters. Furthermore, both magnetic fields and high-energy electrons may have been stored with these plasmas in this spherical region. Although such an idea was of much interest, however, it has later been made clear from radio observations that the radio intensity in the direction $l=0^\circ$ and $b=\pm45^\circ$ is at most 1 per cent of that from the galactic center. Based on this result and others, the idea of the halo was eventually dissolved.\textsuperscript{13}

The life $\tau$ for cosmic rays to be confined in the galactic disk has been estimated as $\leq 10^7$ years ($\tau \leq 10^7$ yrs), based on the assumption that cosmic rays propagate through a medium where the mean particle density is about $1$/cm$^3$ (see Chapter 4 for the detail). On the other hand, if cosmic rays were confined in the halo where the particle density seems to be $10^{-2}$/cm$^3$, the life $\tau$ would be longer than $10^5$ years, since cosmic rays must have passed through a total length of $5$ g/cm$^2$ in such a low density region. If this is the case, the gradient of the energy spectrum of high-energy electrons would change slope at an energy around 3 GeV, as evident from Eq. (5.4.6). However, there
is no evidence of such a change in the spectrum.

From the analysis on the relative abundance of $^{10}$Be isotopes, whose half-life is $1.6 \times 10^6$ years, in the secondary components of cosmic rays, it has been estimated that $\tau$ is about $3 \times 10^6$ years within the region of about 1000 pc around the solar system (see Section 4.3). From these results on the life of cosmic rays, the model of the galactic halo is not considered as acceptable, though it is very interesting. Since any model like the halo is closely related to various aspects of galactic structure, the validity of the galactic halo may be said to be still in question. It may be noted that the recent observations by radio waves are highly suggestive of the existence of an extended envelope of high-temperature plasmas surrounding the galaxy.

5.5 The Crab Nebula—A Supernova Remnant

5.5.1 The structure of the Crab nebula

One of the most powerful radio sources in the Galaxy is the nebula known as the Crab nebula in the constellation Taurus (Fig. 2.2.10). This nebula is well known as the remnant of the supernova which exploded in 1054 A.D., and, even now, is still brightening in an oblate area of angular extension 6 and 4 arc-minutes in the long and the short axes, respectively. As regards the optical spectra from the nebula, many lines are superposed on the continuous spectrum. The photographic picture taken in hydrogen H$_a$ light shows the characteristic filamentary structure of this nebula as seen in Fig. 5.5.1(a). It thus seems that this structure reflects the real nature of this gaseous nebula. The elements constituting this nebula can be estimated from spectroscopic studies of the line spectra from the nebula.

Since the continuous emissions from the nebula are highly polarized, many of the different properties hidden in the nebula can be clarified by taking pictures of the nebula in different planes of polarization by using a polarized filter. It seems that the observed polarization of the optical emissions are caused by the synchrotron radiations from high-energy electrons interacting with the magnetic field in the nebula. If this is to be the case, the magnetic structure of this nebula can be deduced, though roughly, since the optical radiations from the synchrotron processes are highly polarized in the direction perpendicular to the magnetic field. Figure 5.5.1(b) shows the directions of the polarization vectors perpendicular to the line of sight in the nebula, which have been obtained by Woltjer. The directions of the magnetic vectors are not random, but seem to have a kind of wavy structure. By superposing both results as shown in Figs. 5.5.1(a) and (b), it follows that the Crab nebula seems to be constituted of several large-scale structures such as bubbles or cells.

The structure of the Crab nebula as observed by radio waves is shown in Fig. 5.5.1(c). This nebula is also seen as an extended brightening area by X-rays. Though it is not easy to look for the structure seen by X-rays, the structure as shown in Fig. 5.5.2 has been obtained by the large X-ray telescope, the so-called “Einstein Observatory” (<3 keV) and the Japan-U.S. cooperative balloon observations with the “sudare” collimators (20–40 keV).

X-rays also seem to be emitted by the synchrotron mechanism since they are
polarized in the same way as the optical emissions. As expected from Eq. (5.4.9), high-energy electrons are trapped by the magnetic fields of the nebula and the energies given by $1.25 \, \text{MeV}/\sqrt{B} \times 1.25 \times 10^4 \, \text{MeV}/\sqrt{B}$ and $1.25 \times 10^6 \, \text{MeV}/\sqrt{B}$ correspond, respectively, to the radio, optical and X-ray emissions, where $B$ is measured in units of gauss. If the field intensity is assumed to be $3 \times 10^{-4}$ gauss, these energies are, respectively, calculated as $5 \times 10^{-7} \, \text{eV}$, $5 \times 10^{11} \, \text{eV}$ and $5 \times 10^{13} \, \text{eV}$.

5.5.2 The combined spectra for radio, optical light and X-rays

A synthetic flux spectrum from radio, via optical light, to X-ray emissions is shown in Fig. 5.5.3. In the frequency range between $10^7$ and $10^{13}$ Hz, connecting radio with optical emissions, this spectrum is expressed as $f^{-0.28}$, where $f$ is the wave frequency. Thus, the differential energy spectrum of electrons is obtained as $E^{-1.56} \, dE$. As seen in this figure, this spectrum becomes sharply bent in the infrared frequencies around $10^{13}$ Hz and, as a result, is expressed as $f^{-1.15}$ in the X-ray region. The integration of this spectrum with respect to frequency gives a total energy flux of the order of $10^{-7} \, \text{erg/cm}^2 \, \text{sec}$. Since the distance of the Crab nebula is estimated as about 4500 light years, the total amount of radiation energy is calculated to be $10^{-7} \times 4\pi$ (4500 light years)$\approx 2.5 \times 10^{37} \, \text{erg/sec}$. Thus, this nebula loses energy of about $10^{45} \, \text{ergs}$ in a year and $10^{49} \, \text{ergs}$ in $10^4$ years, in the form of radiation.

From the observed Doppler shifts of the optical line emissions, it is known that the speed of expansion of the nebula is about 1000 km/sec. If we assume that the total mass of this nebula is of the same order as that of the sun, the kinetic energy contained in this expanding motion is about $10^{49} \, \text{ergs}$. This value is of the same order of the amount of radiation energy emitted during $10^4$ years. Although only a thousand years have passed since its birth, the Crab nebula appears to have been highly active for more than $10^4$ years, as expected from observations on other supernova remnants.

When the distance of the Crab nebula from us is denoted by $D(m)$, the observed intensity of the synchrotron radiation can be written as

$$ J = \frac{2.4 \times 10^{-24}}{4\pi D^2} V \cdot K \cdot B^{(p+1)/2} (6.26 \times 10^{18})^{(p-1)/2} f^{(p-1)/2} (\text{W/m}^2\cdot\text{Hz}), \quad (5.5.1) $$

where $V(m^3)$ denotes the volume of the nebula. The magnitude of $K$ can be calculated from the observed intensity as $J \approx 1.5 \times 10^{-23} \, \text{W/m}^2\cdot\text{Hz}$ at $f = 10^8 \, \text{Hz}$ by referring to Eq. (5.5.1).

5.5.3 The total energy of ambient electrons

The total energy shared by electrons in the Crab nebula is given by

$$ W_e = V \int_{E_1}^{E_2} KE^{-7} \cdot EdE. \quad (5.5.2) $$

After substituting the numerical value of $K$ obtained above into this equation, this equation is integrated with respect to the energy range between $E_1$ and $E_2$. These two energies correspond to the frequencies at $10^7$ and $10^{13} \, \text{Hz}$, respectively. The result
Fig. 5.5.1.
Fig. 5.5.1. (a) The Crab nebula as observed by the hydrogen Hα-line emissions. (b) The polarization of the light from the Crab nebula. (c) The Crab nebula as observed by the radio emissions.

Fig. 5.5.2. The Crab nebula as observed by the X-ray emissions.
of this integration is thus given as

$$W_e \approx \frac{4 \times 10^{43}}{B^{3/2}} \text{ ergs.}$$  \hfill (5.5.3)

In the frequency range higher than the frequency corresponding to optical radiation, the differential energy spectrum of the electrons is so sharply bent that the contribution from this region \((E > E_2)\) is very small to the energy calculated as in Eq. (5.5.3). Assuming that \(B \approx 3 \times 10^{-4}\) gauss, it follows that \(W_e \approx 10^{49}\) ergs. It is interesting to note that this amount of electron energy is nearly equal to the energy of the nebular expansion and also to the total energy expected to be radiated over \(10^4\) years.

5.5.4 **Magnetic fields in the nebula**

There is no observed evidence of a magnetic field in the Crab nebula, though a magnitude of \(B \approx 3 \times 10^{-4}\) gauss has been assumed. Several items of indirect evidence support this.

(1) We first assume that there exists a close correlation between electrons and magnetic fields in the Crab nebula. While these electrons are trapped by the magnetic fields “frozen” in the nebular plasmas, it may be thought that these magnetic fields are partly deformed or put in motion due to the action of these electrons. If an equilibrium state is attained between the electrons and the magnetic fields, the sum of the total energy \((W_e)\) of these electrons and of the magnetic energy \((W_b)\) is constant. Thus the variation of this total energy must be zero; namely,

$$\delta(W_e + W_b) = 0.$$
Since $W_c \propto B^{3/2}$ and $W_B \propto B^2$, it follows that $W_B = 3/4 \ W_c$. Using the relation $W_B = (B^2 / 8\pi) \cdot V$ and Eq. (5.5.3) and taking the nebular volume $V$ as $V \sim 10^{56} \text{ cm}^3$, the magnetic intensity is estimated as

$$B \sim 5 \times 10^{-4} \ \text{ gauss.}$$

(2) The observed sharp bending of the frequency spectrum of the radiation from the Crab nebula can be interpreted by assuming that the higher energy part of the electrons is lacking from the original spectrum as a result of the loss of their energy by the synchrotron radiation during $10^7$ years. The life due to the energy loss by this process is given from Eq. (5.4.1) as

$$\tau = \frac{E}{-\frac{dE}{dt}} = \frac{E}{aE B^2 E^2}$$

$$\approx \frac{1}{2 \times 10^{-3} \ E(\text{erg}) \cdot B^2(\text{gauss})} \ (\text{sec}).$$

The frequency $f_0$, at which the observed frequency spectrum is sharply bent, is estimated, using Eqs. (5.4.9) and (5.5.4), as

$$f_0 \approx 3 \times 10^{23} / \tau^2 \cdot B^3 \ (\text{Hz}).$$

Assuming that $f_0 \approx 10^{13} \ \text{Hz}$ and $\tau \sim 3 \times 10^{10} \ \text{sec}$ (1000 years), the magnetic intensity is deduced as $B \sim 3 \times 10^{-4} \ \text{gauss}$. 

(3) Based on the assumption that $\gamma$-rays from the Crab nebula are produced by the inverse-Compton scattering of photons ambient in the nebula and 3 K background photons by high-energy electrons in the nebula, Fazio and others have estimated the upper limit of the density of these electrons by referring to the maximum possible flux of the observed $\gamma$-ray emissions. Then, they have deduced that the lower limit of the magnetic intensity may be given as $5 \times 10^{-4} \ \text{gauss}$.

In these three cases, it seems the most plausible to take the intensity of the magnetic fields in the nebula as $(3 \sim 5) \times 10^{-4} \ \text{gauss}$. So far we have considered that the magnetic fields are uniform in the nebula, but, really speaking, it seems that there are a lot of varieties in the structure of magnetic fields. As will be discussed later, it sometimes seems necessary to consider that a magnetic cavity is formed in the central portion of the nebula.

5.5.5 Energy sources of the Crab nebula

The most important question is perhaps on the energy sources of the nebula. An idea that the energy released from the supernova explosion was initially stored in the nebula as gas motion there has been proposed, but it encounters several difficulties. As will be considered later, there is evidence to show that energetic particles are being actively accelerated even now, and also the optical observations indicate the motion
called “ripples” in the central portion of the nebula (Fig. 5.5.4). In fact, these ripples are propagating away from the two central stars near the center of the nebula with a speed of about one-tenth that of light. This suggests that, even at the present moment, some active phenomena are taking place in the nebula and its environment.

The other candidate for the energy source may be the rotational energy of the neutron star found near the center of the nebula. This star, identified as the pulsar PSR0531+21, is seen in the emissions of radio waves, optical light and X-rays, and is now rapidly rotating with a period of about 33 msec. This pulsar is identified as the southern one of the two stars located at the central portion of the nebula. The period of this pulsar has been becoming longer at the rate of $1.4 \times 10^{-5}$ sec per year; in other words, the rotating speed of this star is slowing down gradually with time. The energy of the rotation is, in fact, being dissipated into the surrounding space.

If we take the radius and the mass of the neutron star as 10 km and $10^{33}$ g, respectively, this energy of rotation is obtained as

$$U = \frac{1}{2} I \omega^2 \approx \frac{1}{2} \times 10^{45} \text{ (g} \cdot \text{cm}^2) \cdot \left(\frac{2\pi}{0.033}\right)^2 \approx 2 \times 10^{49} \text{ ergs.}$$  \hspace{1cm} (5.5.5)$$

This energy is of the same order as the kinetic energy of the nebula itself and also with the total energy of electrons $W_e$. The lapse rate of the rotation energy is calculated as

$$- \frac{dU}{dt} = U \frac{dT}{dt} / T,$$  \hspace{1cm} (5.5.6)$$

Fig. 5.5.4. The schematic diagram for the central part of the Crab nebula as viewed from the optical emissions. It is clear that ripples are moving farther away from the central neutron stars.
where $T$ is the period of the rotation of the central neutron star and has been given numerically as $T=0.033$ sec. Since $\frac{dT}{dt}=-4.3 \times 10^{-13}$, the above rate is calculated as

$$\frac{dU}{dt} \approx 10^{38} \text{ erg/sec.} \quad (5.5.7)$$

Even when this rotation energy alone is considered as the source of the nebular activities, it is clear that this rate is enough to supply the whole energy of the radiations from the nebula.

When it is assumed that the life for the central neutron star to continue to actively rotate is given as $T/(dT/dt) \approx 0.033/4.3 \times 10^{-13} \approx 10^{11}$ sec., the total amount of the energy released from this star due to its rotation amounts to $10^{38} \text{ erg/sec} \times 10^{11}$ sec $= 10^{49}$ ergs. Assuming that this energy is effectively supplied to the acceleration of cosmic rays and that the frequency of occurrence of supernova explosions is once every fifty years, the energy acquired by cosmic rays is estimated to be $10^{49}/50 \times 3 \times 10^7 = 10^{40}$ erg/sec on the average. This rate is fully enough to supply the energy of cosmic rays which is lost from the Galaxy (see Chapter 4).

It seems possible, therefore, to take up a hypothesis that the energy released from supernova explosions is first stored as the rotation energy of central neutron stars and then expended in various activities in the Galaxy such as the origin of cosmic rays. Really speaking, it is interesting to note that a kind of equilibrium state is fulfilled among three different types of energy related to the motion of nebulae, the radiation from nebulae and of the energy of cosmic rays. In consequence, it seems necessary to consider the possible transport processes of the energy between the rotation of neutron stars and the nebulae surrounding these stars. One of these processes, of course, is that which is related to particle acceleration by the rotating motion of these stars.

### 5.5.6 High-energy electrons

Since all radio waves, optical light and X-rays radiated from the Crab nebula are strongly polarized, it seems that most of the radiant energy is released through the synchrotron process. If we assume the magnetic intensity to be $3 \times 10^{-4}$ gauss, the life for high-energy electrons to lose the most of their energy by this process can be estimated using Eq. (5.5.4) as $\sim 100$ years and several months to years for electrons of energy $\sim 10^{12}$ eV and $\sim 10^{14}$ eV, respectively, which correspond to optical and X-ray emission. If it is allowed to assume that the Crab nebula is in a steady state, it is necessary to find a mechanism to accelerate electrons to high-energy in an extremely short time. The Fermi mechanism has long been considered as one of the dominant mechanisms of the acceleration of cosmic rays.

The Fermi mechanism is favorable to introduce the power law energy spectrum of the accelerated particles. Denoting the mean scale-length of magneto-turbulence (a random scatterer of particles), the mean speed of this turbulence and the life of the accelerated particles with $l$, $u$ and $\tau$, respectively, the energy spectrum of the accelerated particles is given, as a result of the stochastic process, by
\[ N(E) \, dE \propto E^{-\gamma} \, dE, \]  

(5.5.8)

where \( \gamma = 1 + (1/\alpha \tau) \) and \( \alpha \equiv \alpha^2/cI \), in which \( c \) is the speed of light. Since the observations indicate that the power index \( \gamma \) is of the order of 2, it follows that \( \alpha \tau \sim 1 \). In the case of high-energy electrons, this life \( \tau \) is estimated to be of the order of \( 10^7 \) sec and \( 10^9 \) sec for X-ray and optical emissions, respectively. Consequently, the values of \( \alpha \) corresponding to these two results are obtained to be of the order of \( 10^{-7} \) and \( 10^{-9} \) in this order. Since it seems that the speed of the turbulent motion in the nebula is of the order of \( u \sim 1000 \) km/sec, the numerical values of \( I \) for these two cases are, respectively, \( 3 \times 10^{14} \) cm and \( 3 \times 10^{12} \) cm. Such turbulent motion as assumed above has to be strong enough for high-energy particles to be effectively scattered, because the speed considered is too low to explain the observed energy spectrum as given in Eq. (5.5.8). However, it seems impossible to find such high-speed motion in the nebula observationally. In fact, it is necessary to assume some unlikely motion in these magneto-turbulences with much higher speed. As a consequence, it is required to find some acceleration mechanism much more efficient than Fermi mechanism.

The difficulty as mentioned above had gradually become clear in the late 1960s, while the important alternative idea was put forward which took into account the role of pulsars or rotating neutron stars as the effective accelerator of cosmic rays. It seems plausible to suppose, though being qualitative, that charged particles would be efficiently accelerated in association with the rapid rotation of the central neutron stars because there seems to exist a strong magnetic field of \( 10^{12} \) gauss on the surface of these stars. At the present moment, various mechanisms have thus been studied on the acceleration mechanism of high-energy particles by rotating neutron stars. A probable mechanism will be briefly considered in the next section.

### 5.5.7 Particle acceleration by the pulsar

Before the discovery of pulsars, Pacini had shown theoretically that a neutron star rapidly rotating with its magnetic field will powerfully radiate electromagnetic waves with the same frequency as the rotation frequency due to the mechanism of the magnetic dipole radiation.\(^{15}\) This mechanism would be explained intuitively as follows: the tork appearing as the result of the above rotation is expressed as

\[ N = - \frac{2(msina)^3}{3c^3} \Omega^3, \]  

(5.5.9)

where \( m \), \( a \) and \( \Omega \) are the magnetic dipole moment, the angle between the rotation axis and the dipole vector, and the angular velocity of the star, respectively. This moment is calculated as \( B_0 \pi R^3 \) when the intensity of the magnetic field is \( B_0 \) on the surface of the star of radius \( R \). According to Pacini\(^{15}\) and Ostriker and Gunn\(^{16}\), since the stellar rotation is slowed down due to the above tork, the magnetic intensity \( B_0 \) is calculated, by referring to the rotation period \( P \) and its rate of change \( \dot{P} \), as
\[
B_0 \approx \left( \frac{3Ic^3 P \dot{P}}{8\pi^2 R^6} \right)^{1/2} .
\] (5.5.10)

Substituting the numerical values \(I=10^{45} \text{ g}\cdot\text{cm}^2\) and \(R=10 \text{ km}\) into the above equation and counting \(P\) in unit of seconds, \(B_0\) is calculated as

\[
B_0 \approx 3.2 \times 10^{19} (P\dot{P})^{1/2} \text{ gauss.}
\]

Substituting, further, the measured results of \(P\) and \(\dot{P}\) for several pulsars into the above result, it follows that the magnetic intensity \(B_0\) is of the order of \(10^{13}\) gauss for those pulsars. Therefore, this result agrees well with the intensity of the magnetic field deduced theoretically for neutron stars.

Ostriker\(^{17}\) and others had shown that, after the accelerated particles had acquired an energy higher than some critical one, they would be further accelerated continuously by being trapped steadily in a region with a constant phase of the radiation electric field which would be strong enough since the magnetic dipole radiation must be very powerful. This acceleration mechanism, called analogously the “surfing” mechanism, seems to be able to produce particles of energy up to \(10^{12} \text{ eV}\). It should, however, be noted that this mechanism only functions efficiently in the region distant away from the neutron star.

In the meantime, Goldreich and Julian had shown that, when a highly conductive star with a strong magnetic field rotates around its magnetic axis, a strong electric field is induced around the central neutron star along the magnetic lines of force.\(^{18}\) This phenomenon could be qualitatively interpreted as a sort of unipolar induction, from which the electromotive force is induced by connecting a rotating dipolar magnet with its side by means of conductive wire. The electric field thus induced along a magnetic line of force at the surface of the star is given by

\[
E_\parallel \approx \frac{\Omega R}{c} B_0 \approx 6 \times 10^{10} P^{-1} \text{ (V/cm)} .
\]

Numerically, this field becomes of the order of \(10^{12} \text{ V/cm}\). This field is so strong that it can pull both protons and electrons out of the surface of the star into the outer region. From this result, Goldreich and Julian hypothesized that such a sort of plasma region might have been formed round the neutron star and its nearby domain, and this region would corotate with the star by being confined by the strong magnetic field. The rotating speed becomes higher in proportion to the stellar radius and eventually reaches the speed of light. A cylinder rotating with the speed of light, called a “light cylinder”, is formed eventually around the neutron star. Beyond this cylinder, the plasmas are unable to rotate with the central star at the speed of light. Thus the magnetosphere surrounding the neutron star seems to have a structure as shown in Fig. 5.5.6. In this figure, the shaded area consists of the plasma region corotating with the central star, but the magnetic lines of force extending beyond the light cylinder form the toroidal configuration along the surface of this cylinder.
In Fig. 5.5.5, the rotation axis of the neutron star is taken as perpendicular to the magnetic axis, while, in Fig. 5.5.6, both of these two axes are taken as being parallel to each other. In general, it seems that these two axes are neither perpendicular nor parallel to each other, however. In the outer region close to the neutron star, there may exist a plasma region rotating with the magnetic field, whereas electromagnetic waves seem to be generated by the magnetic dipole in the region distant from the star. To connect this plasma region with these distant waves has not yet been solved, but it is possible to interpret it qualitatively as mentioned above. Thus, rotating neutron

![Diagram](image1)

Fig. 5.5.5. The magnetic dipole radiations around the Crab pulsar.

![Diagram](image2)

Fig. 5.5.6. The plasmas around the rotating neutron star.
stars are probably able to accelerate high-energy particles like cosmic rays and lose their rotating energy due to the ejection of a mass of plasmas. The activities seen in the Crab nebula seem to be driven by such a process.

One more mysterious question appears when we assume that neutron stars are responsible as the sources of high-energy electrons. If the magnetic field of the Crab nebula is assumed as $3 \times 10^{-4}$ gauss, for instance, the life of high-energy electrons which lose their energy by the X-ray emissions by means of the synchrotron mechanism is estimated as only several weeks. In spite of this estimation, the size of the X-ray source is now extended to the region with the radius of about one light year. This is quite a dilemma. In order to resolve this question, it seems possible to suppose that there exists a large cavity surrounding the neutron star where there is no magnetic field. According to this idea, high-energy electrons hardly lose any energy in the cavity because they are able to move directly without magnetic deflection, and then they begin to interact with the magnetic field once they reach the magnetic wall of the cavity.

In fact, the observed data on the Doppler shifts seen in the nebular gas motion and associated filamentary structure in the Crab nebula suggest that the structure of an "oblate spheroid" seen around the neutron star is expanding outward and that its central part appears much darker than the outer region. This structure may be identified as the cavity described earlier. If this idea is acceptable, it seems that high-energy electrons ejected from the central star after acceleration are now pushing away surrounding plasmas and magnetic fields "frozen" in these plasmas into outer space. Therefore, these plasmas and magnetic fields seem to frame the cavity.

Based on the idea that such a phenomenon as described above could be made clear, to some extent, by the observations of the structure of the Crab nebula with

![Fig. 5.5.7. A model of the structure for the Crab nebula.](image-url)
high-energy X-rays, the cooperative balloon observations of the nebula by hard X-rays of energy $20 \sim 60$ keV was done by the Institute of Space and Aeronautical Sciences, University of Tokyo and the University of California, San Diego in 1977 and 1978. Figure 5.5.7 shows the model of the neutron star deduced from the results of the observations. This model consists of the donut-like magnetic and plasma rings pushed away perpendicularly from the rotation axis of the neutron star, which is rotating around the axis parallel to the long axis of the nebula. It seems, therefore, that high-energy electrons being ejected outward from the neutron star first encounter these rings and then begin to radiate X-rays by the synchrotron mechanism. As a result, this side of these rings is seen as being illuminated by these X-rays. The experimental result and its interpretation are still preliminary. Based on more exact observations in the coming years, the relation of the rotating neutron star with the activities of the Crab nebula as a whole will be made clear.

REFERENCES

I. Literature cited


II. General references