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ANTARCTIC RADIO TELESCOPE FOR ATMOSPHERIC CHEMISTRY AND RADIO ASTRONOMY

Satoshi OCHIAI[1], Tetsuo HASEGAWA[2], Harunobu MASUKO[1], Katsuhide MARUBASHI[1], Masahiko HAYASHI[2] and Masaki EJIRI[3]

[1] *Communications Research Laboratory, 2-1, Nukui-Kitamachi 4-chome, Koganei 184*
[2] *Institute of Astronomy, University of Tokyo, Mitaka 181*
[3] *Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: The Antarctica is an extremely attractive site for ground-based sub-millimeter wave remote sensing and radio astronomy. In particular, a very low water vapor concentration of the Antarctic atmosphere is advantageous in millimeter and sub-millimeter wave observations of the upper atmosphere and astronomical objects. A radio telescope under our planning will be the first Japanese millimeter wave instrument in the Antarctica.

The telescope has an antenna of 60 cm aperture diameter with low noise superconducting receivers covering the frequency range from 200 to 280 GHz. This telescope has two main missions, atmospheric chemistry and astronomy. In atmospheric chemistry, chlorine monoxide and hydroperoxyl, which are concerned with ozone chemistry, will be observed. In astronomy, observation of Milky Way of southern heaven and Magellanic Clouds at 230 GHz of carbon monoxide emission line is an important subject.

The telescope is now under development at the Communications Research Laboratory in collaboration with University of Tokyo. The millimeter wave observation will start in 1994 at Syowa Station.

1. Introduction

The short-millimeter and sub-millimeter wave region, that is the frequency region from 100 to 3000 GHz, contains many spectral lines of molecules which are important species in atmospheric chemistry and astronomy. The lower atmosphere is not sufficiently transparent for observing weak molecular emission from the sky in this frequency range, because of a strong absorption by water vapor. The site with low water vapor concentration is desirable for observations in this frequency. Some efforts have been made in the world to construct millimeter wave telescopes at suitable sites, such as the summit of Mauna Kea, Hawaii. The Antarctica is one of the best sites with low water vapor concentration.

The observations in the Antarctica is scientifically meaningful in both the atmospheric research and astronomy. The 'ozone hole' problem is a big topic in stratospheric ozone science. The monitoring of ozone and other related minor constituents, which have spectral lines in the millimeter wave region, is essential to construct a reliable chemical model for the earth's atmosphere. A continuous monitoring is possible only by a laser radar or millimeter wave radiometer.

Beyond the earth's atmosphere, we can find numerous interesting astronomical objects which are accessible only from the southern hemisphere of the earth. Above all, the Large and Small Magellanic clouds, the two satellite galaxies of the Milky Way Galaxy, offer a great amount of invaluable information on star formation and evolution of galaxies, the major topics in astrophysics.

In a strong contrast to these scientifically motivated needs, the number of radio telescopes operated at wavelengths as short as one millimeter is extremely limited.

The instruments needed to monitor atmospheric chemical species are very similar to those for astronomical line observations. Both of them use the same frequency range which is the windows for water vapor or oxygen absorption bands. The instruments need a high sensitivity, a high frequency resolution and a high stability. The specifications required for both atmospheric chemistry and astronomy are almost identical. The major difference between two requirements is the antenna size. The antenna with large aperture diameter (≈ 10 m) is often preferred for astronomical observation, whereas several tens centimeters of the diameter is enough for atmospheric observations. Nevertheless, a small antenna for atmospheric observations is still useful for astronomical observations, such as the survey of the Milky Way and the Magellanic Clouds. Other differences are that the astronomical instrument needs higher precision in pointing the antenna direction, and that atmospheric one needs a larger band width of spectrometer and an additional reference temperature noise source.

We are developing a 1-mm wave radio telescope system with a 60-cm diameter antenna, which can be used both for atmospheric monitoring and for astronomical observations. This system is designed to be put at Syowa Station in the Antarctica to make a continuous monitoring of the ozone hole and observations of important southern astronomical objects.

In this paper we discuss the scientific aims of our project with a brief description of the instrument.

2. Atmospheric Observation

2.1. *Chemistry in Antarctic stratosphere*

There are several chemical species which can be detected by millimeter wave emission observation. Some species of hydrogen, nitrogen and chlorine oxides play very important roles in the ozone depletion mechanism. In the spring Antarctica, a rapid decrease of ozone is due to the chlorine cycle. According to the ozone hole formation theory in the spring Antarctica (SOLOMON, 1990), Cl is supplied from the inactive compounds, HCl and $ClONO_2$, by heterogeneous reactions on the surface of polar stratospheric clouds, and joins into the chlorine cycle (Fig. 1). The chlorine cycle in ozone hole has two paths. In one path, ClO combines with another ClO to produce Cl_2O_2, in the other path, ClO reacts with BrO. The contribution from the latter path to the total reaction rate in the chlorine cycle is believed about 20%. In both paths, the rate limiting step is the reaction of ClO in the cold and sunlit condition. The rate of ozone loss by the chlorine cycle is

$$\frac{d[O_3]}{dt} = -2(k_1[ClO]^2[M] + k_2[ClO][BrO])$$

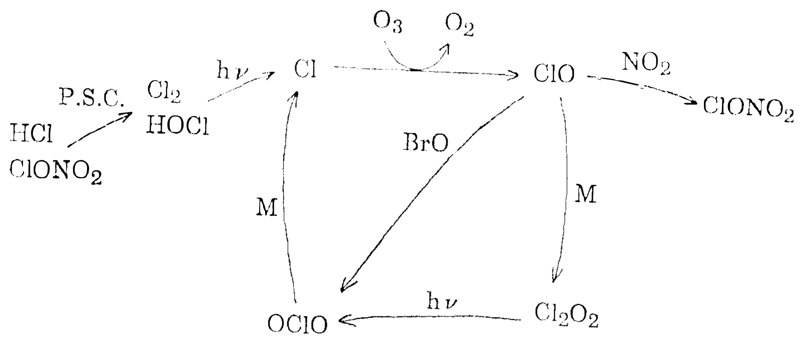

Fig. 1 Chlorine cycle in the lower atmosphere in the spring Antarctica.

where k_1 and k_2 are the rate coefficients, M is any third body. If the rate coefficients and the BrO concentration are assumed, the ozone destruction rate by the chlorine cycle can be estimated directly by measuring the ClO concentration (BARRETT *et al.*, 1988). The ClO concentration at low altitudes in the spring Antarctica is extremely high, and shows very large diurnal variations (DE ZAFRA *et al.*, 1989). Therefore the continuous monitoring of ClO, which has spectral lines around 204 and 279 GHz, makes a great deal of contributions to the ozone chemistry.

The observation of the other species related to the ozone chemistry is important as well as that of ClO. Nitrogen species have an ability to convert active chlorine species into inactive reservoir in the Antarctic atmosphere, although they have other ozone destruction cycles when the amount of chlorine compounds is small.

2.2. *Species to be observed*

Atmospheric ozone has the strongest absorption in the millimeter and sub-millimeter wave region except for water vapor and oxygen. The concentration of ozone can be obtained by measuring the emission intensity at one of hundreds of lines existing from 100 GHz to sub-millimeter wave. Figure 2 shows an example of an ozone emission line centered at 235.70984 GHz. The data represents an observation at noon on February 21, 1991 at the Nobeyama Radio Observatory (NRO), with the telescope of University of Tokyo, which is 230 GHz telescope

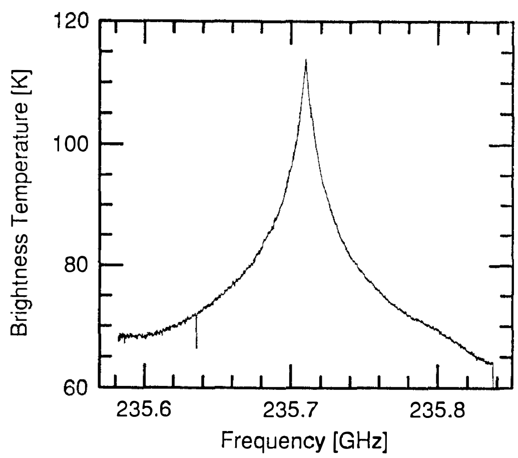

Fig. 2. Ozone emission line observed at the Nobeyama Radio Observatory. The integration time was 200 seconds. Frequency resolution was 0.3 MHz. Sky temperature was approximately coincided with liquid nitrogen temperature varying the elevation angle. The elevation angle was 40 degrees when this data was taken.

with an antenna of 60 cm diameter. It took 200 seconds of integration time to get the data. The data was compensated with signals from the reference noise source integrated for the same length of time. The absorber saturated with liquid nitrogen was placed over the tertiary mirror as the reference noise source. The height profile of ozone concentration in the upper stratosphere can be estimated from this data with an inversion technique.

ClO has spectral lines approximately every 37 GHz in the millimeter and sub-millimeter wave range. The intensity of ClO emission is much weaker than that of ozone, and is approximately a hundred milli Kelvin in the case of ground-based observation. The simulated ClO emission is shown in Fig. 3. The emission of (a) in Fig. 3 is calculated assuming the U.S. standard atmosphere and that of (b) is calculated with the data measured in the spring Antarctica (DE ZAFRA *et al.*, 1989).

ClO in the Antarctic atmosphere had been measured with millimeter wave radiometer (DE ZAFRA *et al.*, 1989) and airborne *in situ* chemical fluorescence (ANDERSON *et al.*, 1989) until now. Both measurements were carried out during the National Ozone Expeditions. These measurements revealed that the ClO concentration in the spring Antarctic lower atmosphere shows an extremely high concentration, and has a strong negative correlation with the ozone concentration. These facts confirmed the chlorofluorocarbon ozone destruction theory. However, the seasonal variation and the relationship of the ClO concentration with the atmospheric dynamics are not yet clear in the Antarctica.

To understand atmospheric chemistry quantitatively, chlorine, nitrogen, and hydrogen species must be monitored simultaneously with ozone and ClO. The intensity of emissions of these species are similar to the case of ClO or less. Our plan will allow for observation of HO_2, N_2O, HNO_3, NO, NO_2 and CO in addition to ozone and ClO.

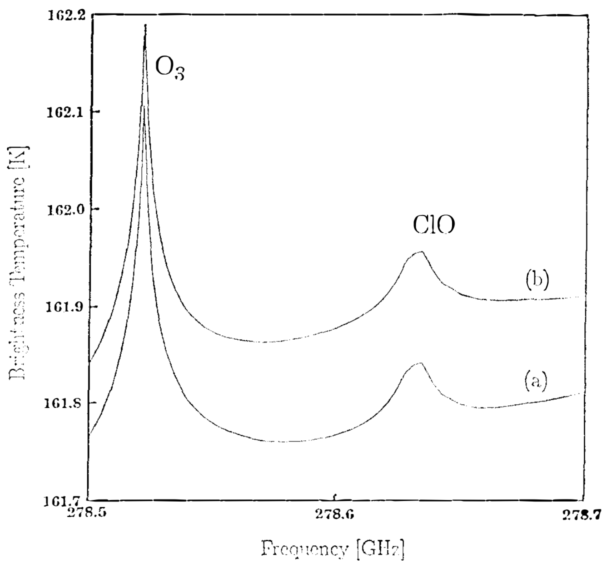

Fig. 3. Simulated ClO emission line. The U.S. standard atmosphere is assumed. (a) the standard ClO is used. (b) the ClO concentration measured by DE ZAFRA *et al.* (DE ZAFRA *et al., 1989*) *is used.*

3. Astronomical Observations

3.1. *Viewing the Milky Way Galaxy as a galaxy*

The Milky Way Galaxy has been presumed as a typical giant spiral galaxy with a modest rate of star formation of a few $M_\odot$ per year ($M_\odot = 1.99 \times 10^{30}$ kg; the mass of the Sun). In studies of other galaxies, comparison with the Milky Way Galaxy is often made to evaluate, for example, the mass and the physical condition of the interstellar material, or the star formation activity. Indeed, most known types of the astronomical objects are found in the Milky Way Galaxy within the reach of our detailed observations; stars at various evolutionary stages, globular star clusters, supernova remnants, black holes, interstellar gas and dust in various thermal phases, energetic cosmic ray particles, or even an active galactic nucleus (much less energetic than typical AGNs such as quasars, though). Surprisingly, however, it remains unclear how the Milky Way Galaxy would appear as a galaxy when it is observed from a distant point. This situation has been caused partly by our naturally biased attention to smaller scale structures which led to construction of many large telescopes with the highest spatial resolution permitted by the contemporary technology.

We propose an alternative approach to the Milky Way, *i.e.*, observations of its large scale structure by small telescopes. In radio astronomy, in which we generally operate telescopes in diffraction limited regime, the beamsize of a telescope scales with its diameter inverted. For the observations of extended sources such as the Milky Way, this large beam solid angle compensates the small aperture collecting area of the telescope, so that the sensitivity of the telescope system becomes independent of its size. The large beam makes it possible to survey the Milky Way, which covers a significant fraction of the sky, in a reasonable observing time.

Similar approach has been taken by pioneering work by S. Kodaira, J. Inatani, and collaborators at Kisarazu Technical College, Japan who built a 1.5-m telescope, and by a group led by P. Thaddeus in Columbia University, U.S.A., who built a 1.2-m telescope. Both of the telescopes were operated at 110–115 GHz, the frequencies of the $J=1$–0 transitions of $^{12}C^{16}O$ and $^{13}C^{16}O$. The Columbia group used the 1.2-m telescope to map the Milky Way in the CO line and revealed the mass distribution of the molecular gas in the Galaxy. They subsequently built another 1.2-m telescope and operated it in Chile to observe the southern Milky Way and to complete their whole Milky Way survey (*e.g.*, Dame *et al.*, 1987).

3.2. *The 230 GHz galactic CO survey*

Although the CO $J=1$–0 transition is, in a first order approximation, a tracer of the column density of molecular gas (mainly H_2), observations of this transition alone do not allow us a reliable estimate of the physical conditions of the molecular gas such as density or temperature. Determination of these parameters is important not only from the viewpoint of interstellar physics but also for the improved mass estimate of the interstellar gas in the Galaxy, because the molecular gas mass estimated from the CO intensity depends on the temperature and density of the gas assumed (*e.g.*, Maloney, 1990).

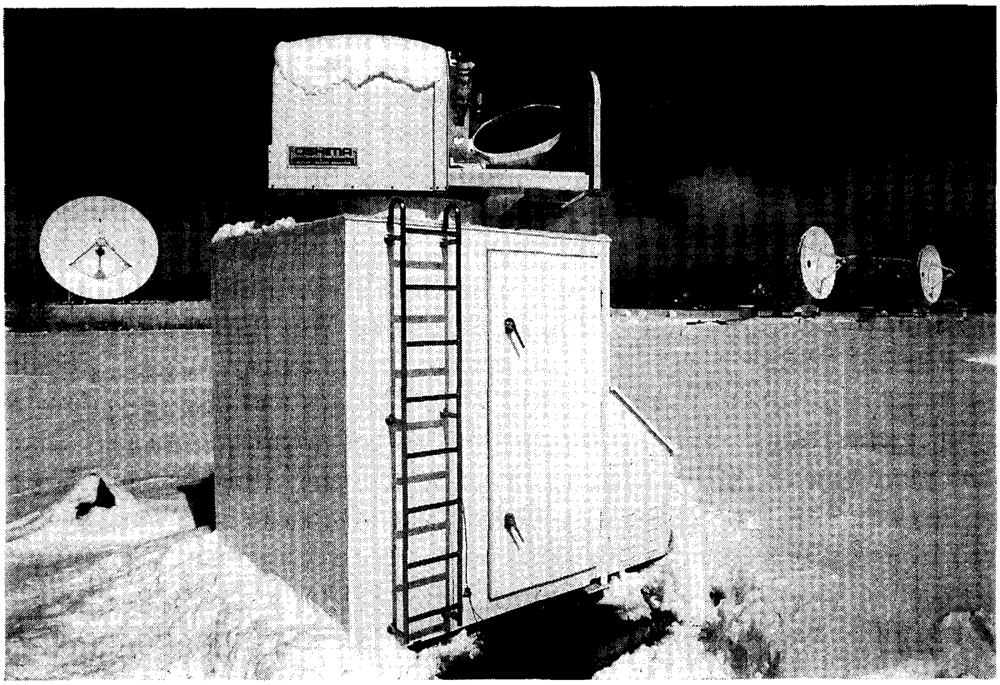

Fig. 4. The University of Tokyo-Nobeyama Radio Observatory 60-cm Galactic Survey Telescope.

Observational estimations of the physical conditions of the molecular gas requires measurements of other transitions of CO or other species such as CS or HC_3N. This approach has been taken in detailed case studies of individual objects. Surveys of molecular gas in the Milky Way Galaxy have been, however, limited to the $J=1–0$ transition of $^{12}C^{16}O$ with little exception, and physical conditions of the molecular gas in galactic scale remain unclear.

To overcome this situation, we started a project to make a galactic survey of the $J=2–1$ CO transition at 220–230 GHz with small telescopes. For the first step, a 60-cm telescope was built in Nobeyama, Japan to make the northern survey (Fig. 4). The diameter of the telescope (60 cm) is chosen to have the beamwidth identical to that of the Columbia 1.2-m telescope at 115 GHz, which enables direct comparison of our $J=2–1$ results with the $J=1–0$ data of the Columbia survey. We started the survey in January 1991, and a rough pilot survey has been made for the first quadrant of the galactic plane (Fig. 5). A preliminary analysis of the data has already revealed a large scale galactic gradient of the $(J=2–1)/(J=1–0)$ intensity ratio (HASEGAWA *et al.*, in preparation). A large scale mapping of two giant molecular clouds in Orion (Fig. 6; SAKAMOTO *et al.*, in preparation), and a detailed mapping of the nuclear molecular cloud complex in the galactic center (OKA *et al.*, in preparation) have also been made.

3.3. *Objectives of Antarctic observations*

If we can put an instrument like the 60-cm telescope in the Antarctica, various interesting astronomical observations become possible. Among these, the southern Milky Way and the Magellanic Clouds are especially important. These objects are

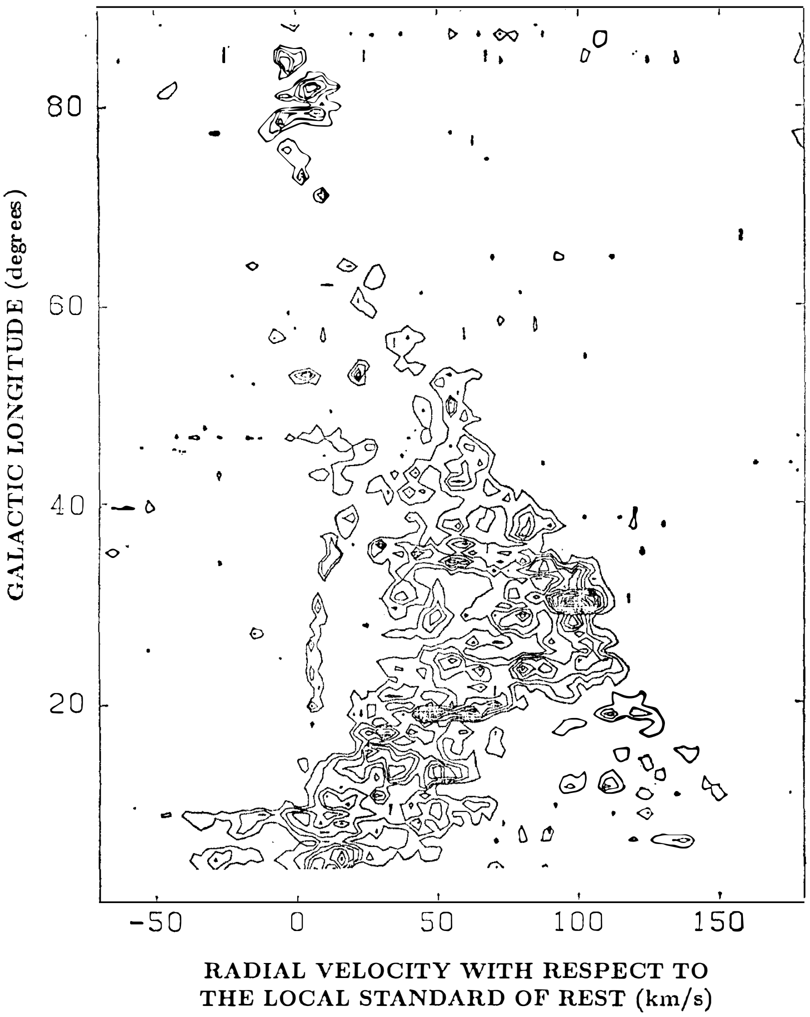

Fig. 5. The galactic longitude-radial velocity plot of the $^{12}C^{16}O$ J=2 − 1 emission at 230 GHz.

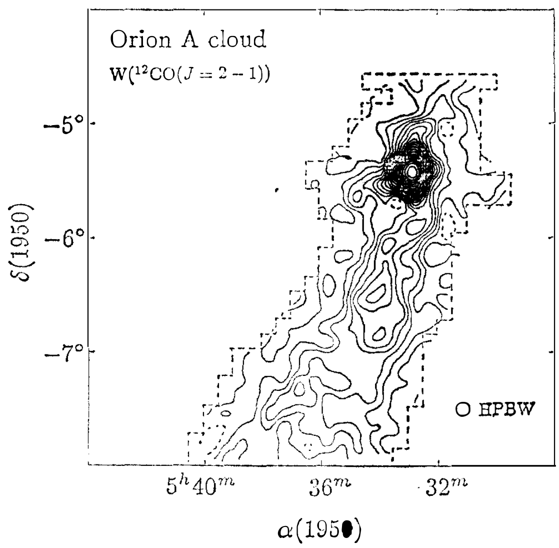

Fig. 6. The map of the $^{12}C^{16}O$ J=2−1 emission from the Orion-A giant molecular cloud (from SAKAMOTO et al., in preparation).

accessible only from the southern hemisphere, and the transparent atmosphere above the Antarctica (especially in winter) makes the observations efficient and accurate.

3.3.1. The southern Milky Way

The Milky Way Galaxy is often assumed as an axisymmetric system to derive various galactic parameters from observations of a portion of the galactic plane. Although this is basically a correct assumption, there exist significant deviations from axisymmetry. For example, it has been reported that the "molecular ring", the most conspicuous feature of the northern Milky Way, appears as a portion of a spiral arm rather than a closed ring when observed in the southern Milky Way. In addition, several region of very active star formation such as η Carinae are found in the southern Milky Way. A survey of these regions in the 230 GHz CO $J=2$–1 emission line and other lines would provide valuable information on the physical conditions of molecular gas on galactic scale and its relation to the star formation activity.

The central region of the Milky Way Galaxy is located at declination $\delta=-28$ degrees in the celestial equatorial coordinate, and more easily accessible from the southern hemisphere than from Nobeyama. Observations of the CO $J=2$–1 line at 230 GHz or other molecular lines (*e.g.*, HCO^+ $J=3$–2 at 268 GHz) would be valuable in determining the physical conditions in the nuclear molecular cloud complex.

3.3.2. The Magellanic Clouds

The Large and Small Magellanic Clouds (LMC and SMC) located at $\delta=-70$ degrees and $\delta=-73$ degrees, respectively, are satellite galaxies orbiting around the Milky Way Galaxy. These are the second nearest galaxies next to the Milky Way and detailed studies are possible.

The Magellanic Clouds are different from the Milky Way Galaxy in many respects. The morphology of the Magellanic Clouds are irregular, and their mass is much smaller than the Milky Way. The abundance of heavy elements relative to hydrogen (metallicity) is much smaller in LMC and SMC than in the Milky Way. Star formation is currently very active in LMC and the radiation field in LMC is more intense than in the Milky Way.

These differences naturally suggest that the physical conditions of the interstellar matter in LMC and SMC are significantly different from that in our Galaxy. Observational test is possible by measuring the $J=2$–1 CO emission and/or other molecular lines from the Magellanic Clouds. As the Magellanic Clouds cover a large solid angle on the sky, a quick survey with a small telescope would be desirable.

4. Millimeter Wave Telescope

Our millimeter wave system has an offset Cassegrain antenna of around 60 cm diameter. The antenna has an azimuth and elevation driving mechanisms, and coudé optics. A radome and a cover of the radome allow operation and survival in the condition of lower temperature and severe wind. The system is possible for operation in the condition of lower than minus 30°C.

The system has two receivers. The frequency ranges of these are from 200 to 230 GHz and from 250 to 280 GHz. The millimeter wave signal from the antenna is divided into two polarizations with wire grid, and fed into two receivers respectively. Each receiver has single side band filter and reference temperature noise source. Superconductor-insulator-superconductor (SIS) junctions are used as low noise mixers. The SIS is mounted in a reduced wave guide, and cooled into 4.2 K. The intermediate frequency is from 5 to 7 GHz. A cooled HEMT amplifier is used for IF stage. Acousto optical spectrometer has 1 GHz of band width, and 1 MHz of frequency resolution.

The SIS mixer is now developed at the Communications Research Laboratory in collaboration with NRO. The radiometer and spectrometers will be completed in 1992. The antenna and the whole of the system will be ready for observation in 1993.

5. Conclusion

Millimeter wave atmospheric science and astronomy are appropriate for research programs in the Antarctica, because they can effectively utilize the characteristics of the Antarctica, *i.e.* very low water vapor concentration in the atmosphere. The telescope that we are preparing to bring to the Antarctica will contribute to the stratospheric ozone chemistry and astronomy in the southern sky. The telescope will be operated in the Antarctica in 1994.

References

ANDERSON, J. G., BRUNE, W. H. and PROFFITT, M. H. (1989): Ozone destruction by chlorine radicals within the Antarctic vortex; The spatial and temporal evolution of ClO–O_3 anticorrelation based on *in situ* ER-2 data. J. Geophys. Res., **94** (D9), 11465–11479.

BARRETT, J. W., SOLOMON, P. M., DE ZAFRA, R. L., JARAMILLO, M., EMMONS, L. and PARRISH, A. (1988): Formation of Antarctic ozone hole by the ClO dimer mechanism. Nature, **336**, 455–458.

DAME, T. M., UNGRECHTS, H., COHEN, R. S., DE GIEUS, E. J., GRENIER, I. A., MAY, J., MURPHY, D. C., NYMAN, L. A. and THADDEUS, P. (1987): A composite survey of the entire Milky Way. Astrophys. J., **322**, 706–720.

DE ZAFRA, R. L., JARAMILLO, M., BARRETT, J., EMMONS, L. K., SOLOMON, P. M. and PARRISH, A. (1989): New observation of a large concentration of ClO in the springtime lower stratosphere over Antarctica and its implications for ozone-depleting chemistry. J. Geophys. Res., **94** (D9), 11423–11428.

MALONEY, P. (1990): Mass determination from CO observations. The Interstellar Medium in Galaxies, ed. by H. A. THRONSON and J. M. SHULL. Dortrecht, Kluwer Academic Publishers, 493–523.

SOLOMON, S. (1990): Progress toward a quantitative understanding of Antarctic ozone depletion. Nature, **347**, 347–354.

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