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The History of Radio Continuum Surveys*

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Abstract. Radio continuum surveys of the sky have been made since the pioneering discovery of cosmic radio emission by Karl Jansky. The all-sky surveys give the basic information about the distribution of radio intensity across the sky. Depending on the angular resolution of a survey we can recognize the emitting regions: the Galactic center, the plane of the Milky Way as well as individual sources, be it H II regions or supernova remnants. In particular the Galactic plane surveys, usually made at higher radio frequencies, allow the delineation of source structure. Polarization surveys add one more parameter and are sensitive to recognize synchrotron emission. In this contribution I will sketch the development of radio sky surveys from the very beginnings at 20.5 MHz up to the wonderful WMAP results at 93.5 GHz.

1 Introduction

The first detection of radio emission of extra-terrestrial origin, made by Karl Jansky, was presented at an URSI meeting in Washington, was featured on the front page of the New York Times (5 May 1933) and was published in the Proceedings of the Institution of Radio Engineers (Jansky, 1933) but was not recognized as a path-breaking discovery by astronomers. The second 'amateur' in this field, Grote Reber, also an engineer, mapped the sky in 1940s at 160 MHz finding the major emission regions to be in the direction of Sagittarius, Cygnus and Cassiopeia. A first rough radio map was published Reber (1944) confounding astronomers because the position of the maximum radio emission was some 30° off the then accepted Galactic center. The years following the Second World War freed many radio engineers and lots of equipment to start a new field of research – radio astronomy. Radio surveys were the first important contributions to be a data base for future work. The development in this field took the logical path, from low radio frequencies to higher ones and from low angular resolution to high resolution. Various types of antennas were used for surveys depending on frequency. More recently satellite surveys at the highest radio frequencies were made. This contribution will describe the history of radio surveys of the sky.

2 The all-sky surveys

In the 1950's many radio surveys at frequencies of 100 to 400 MHz were published. There surveys were usually made with low angular resolution (10°–20°) and had low sensitivity. The surveys were made both in the southern and the northern hemispheres and then joined to all-sky maps. The basic features of the radio morphology of the Milky Way were recognized: the intense emission in the Galactic center, the emission along the Galactic plane as well as 'spurs' of radio emission. Typical of this era, and the first all-sky survey that combined northern and southern data, was made at 200 MHz by Dröge & Priester (1956). The 1960's saw improved angular resolution due to larger antennas becoming available, better dynamic range as a result of better receiver sensitivity and a wider frequency coverage. The angular resolution reached $\sim 1°$ and the data handling became the major problem. An all-sky survey made by Landecker & Wielebinski (1970) used northern sky data from Turtle & Baldwin (1962) and Parkes observations at 150 MHz showing many loop-like structures as well as a great difference between the northern sky and the southern sky. This difference is due to the nearby Perseus spiral arm's proximity relative to the Sun in the northern sky. The 1970's heralded a new era of surveys. Computer techniques were developed to handle large data bases and to display the images. Typical for

*Based on observations with the Effelsberg 100-m telescope operated by the Max-Planck-Institut für Radioastronomie (MPIfR), Bonn, Germany this time is the 408 MHz survey of Haslam et al. (1982) who used three large telescopes: Jodrell Bank Mark I, the Effelsberg 100-m radio telescope and the Parkes 64-m dish for the southern extension, reaching a resolution of better than 1°. The need for well-calibrated data both at higher frequencies and low frequencies was obvious and led to several important contributions. Recent work at 1.4 GHz (W. Reich, 1982; P. Reich & W. Reich, 1986; P. Reich et al., 2001) completed a new all-sky map at this high frequency. Surveys at 45 MHz (Alvarez et al., 1997; Maeda et al., 1998) became also available. A southern survey at 2.3 GHz (Jonas et al., 1985) covered a large section of the Galaxy. On the other end of the frequency scale the 2.1 MHz survey of Reber (1968) must be singled out. Also the satellite era came to fruition with the COBE and WMAP missions giving us all-sky surveys at the highest radio frequencies (22 GHz to 93.5 GHz) with good angular resolution (52′–13′).

3 Galactic plane surveys

During an all-sky survey the Galactic plane is mapped as a matter of course. However the mapping of Galactic plane with higher angular resolution was practiced from the early days of surveying. In fact monumental Galactic plane surveys were published both of the northern and southern sections. I quote surveys of Westerhout (1958), Hill et al. (1958) or Altenhoff et al. (1961) as such historical examples. The development of the subject followed the same way as the all-sky surveys. First lower radio frequency surveys became available, followed by maps at higher frequencies. The angular resolution improved from $\sim 1^\circ$ at the beginning to $1'$ at present. In high-frequency maps the H II regions dominate since they have a flat spectrum. At lower radio frequencies the nonthermal synchrotron emission is clearly seen both diffuse and as sources (SNRs). In surveys at the lowest radio frequencies (e.g. Shain et al. (1961) at 19.7 MHz; Jones & Finlay (1974) at 29.9 MHz; Roger et al. (1999) at 22 MHz) the H II regions are seen in absorption. The most recent surveys of the Galactic plane at highest angular resolution are the 1.4 GHz maps of W. Reich et al. (1990a) and P. Reich et al. (1997), the 2.7 GHz maps of W. Reich et al. (1984, 1990b), Fürst et al. (1990) and the 2.4 GHz maps by Duncan et al. (1995). A limited survey of the Galactic plane at 10 GHz was made by Handa et al. (1987). The many frequencies, especially when the angular resolution is similar, can be used to separate the thermal and nonthermal emission. Also infrared surveys can be used for this purpose (e.g. Fürst et al., 1987). The use of interferometers at 1.4 GHz, notably the Australia Telescope Compact Array (e.g. Gaensler et al., 2001) with an angular resolution of $\sim 1'$ and of the Canadian Galactic Plane Survey (Taylor et al., 2003) with similar resolution, will lead to new horizons, especially when the 'missing spacings' are filled in from the single-dish surveys.

4 Polarization surveys

The linear polarization of the Galactic radio waves is the consequence of the synchrotron emission process. It was discovered by Westerhout et al (1962) and Wielebinski et al. (1962) and was thought to be the 'missing link' in the interpretation of the radio continuum emission. Observations of linear polarization can be used to delineate the morphology of the magnetic fields in the emission regions of our Galaxy. Ionospheric rotation was found to affect the position angle at lower frequencies (Wielebinski & Shakeshaft, 1962). Galactic Faraday rotation was observed by Muller et al. (1963). Large-scale surveys of linear polarization were made at 408 MHz by Wielebinski & Shakeshaft (1964) and Mathewson & Milne (1965). Brouw & Spoelstra (1976) observed a large section of the northern sky at 5 frequencies between 408 MHz and 1.4 GHz that allowed Spoelstra (1984) to make rotation measure studies. New work with higher angular resolution (e.g. Gaensler et al., 2001; Wolleben, this issue) suggests that RMs are much higher than previously published. Also new northern Galaxy observations at 1.4 GHz (Wolleben, this issue) will be combined with a southern polarization survey (Testori, this issue) to give the first complete all-sky polarization survey.

The polarization of the Galactic plane was investigated by Junkes et al. (1987) and more recently by Duncan et al. (1997, 1999). Such studies help immediately to recognize the polarized SNR's as well as some Galactic synchrotron regions. The H II regions are largely unpolarized. Many large maps of selected regions have been published (also in polarization) but to describe them all would surpass the scope of this review greatly, so these results are omitted. The observation of a selected region at 325 MHz by Wieringa et al. (1993) showed considerable structure of polarization intensity that was attributed to Faraday depolarization effects. This was followed up by observations at 1.4 GHz by Gray et al. (1998) and Uyanıker et al. (1999) near the Galactic plane. Also new low-frequency observations have been made (Haverkorn et al., 2000) showing the complexity of the depolarization in the Galaxy. A whole 'zoo' of structures described as 'canals' or 'snakes' were discovered. These studies take a prominent place in the present conference. The action of Faraday screens or of beam depolarization is obvious and may allow us to develop new methods of magnetic field determination (see Wolleben, this issue). The on-going Effelsberg Medium Latitude Survey (EMLS, see W. Reich et al., this issue) will cover $b = \pm 20°$ of the northern Galactic plane with full polarization information. This survey shows that studies of the Galactic plane should not be confined to the narrow strip of $\sim \pm 5°$ since the emission extends from the Galactic disk in to the halo.

5 The future

We have gone a long way from the early surveys to the data sets presently available. Two directions of research are clearly visible. For one we must 'close the gap' between ground based maps (up to 2.4 GHz) and the wonderful WMAP satellite data in the 22–93 GHz range. We need all sky surveys at 5 and 10 GHz with medium angular resolution. This could be achieved with smaller aerials (10–25-m dish) but on an excellent sites with good instrumentation. The Urumqi 5 GHz mapping project discussed in this conference goes in this direction. We badly need the southern extension. Also the now published WMAP data will allow us to study the Galactic plane in greater detail, in particular to allow us to determine the distribution of thermal H II regions. The second direction of endeavor is to understand the rotation measure distribution. We realize its great potential to give us the information about the effects of $B_{\parallel}$ on polarized emission. The combination of radio polarization surveys with data on pulsar and extragalactic source rotation measure should allow us to understand the morphology of the magnetic fields in the Galaxy.

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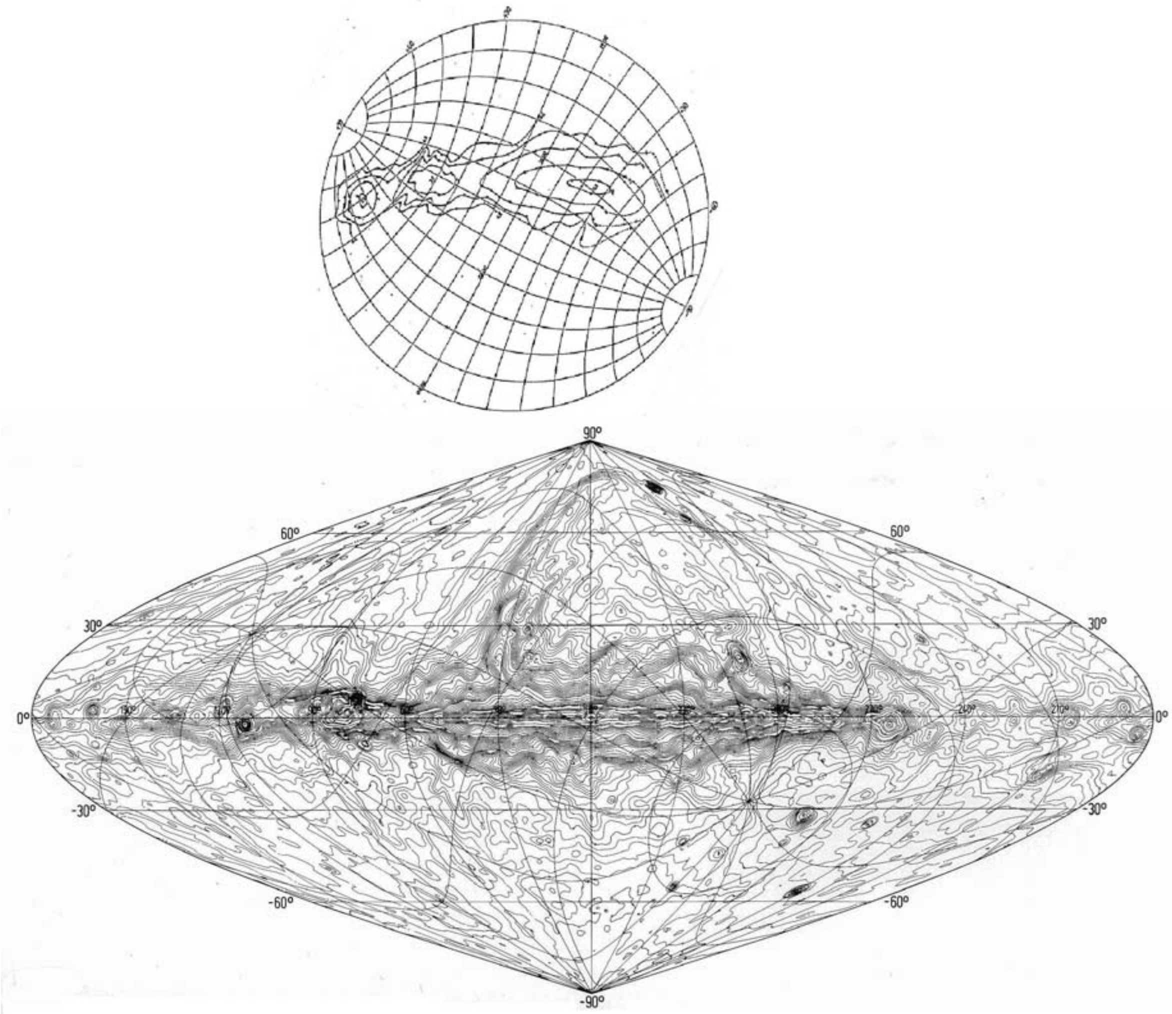

Fig. 1. *Above:* The first 160 MHz radio map of Reber (1944) *Below:* The 408 MHz all-sky survey of Haslam et al. (1982)

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Conference Summary

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The conference dealt with many aspects of the magnetic fields in our Galaxy and nearby galaxies. We had talks about radio polarization observations, about pulsars and extragalactic radio sources as probes of the magnetic fields and about the Zeeman effect which measures the magnetic field in molecular clouds directly. I want to comment on the various contributions in the conference, give some thoughts about what needs to be done in the future and touch on how we could relate our work to the endeavors of our hosts here in Turkey.

The radio continuum surveys are the basic information about the presence of magnetic fields in the Milky Way and nearby galaxies. Since the days of Karl Jansky and Grote Reber, or more correctly since the interpretation of the synchrotron emission process that was given in 1951, we know that the Milky Way is permeated by magnetic fields. Relativistic electrons that come from supernova events or stellar winds produce the radio waves. Radio polarization observations were the final step that confirmed this scenario. We heard a lot about many surveys that are now available for further studies. One curious fact emerges: there are good all sky surveys nicely spaced in frequency from 30 MHz up to 1.4 GHz made from the ground and then excellent new surveys from the WMAP satellite at frequencies from 22.8 GHz to 93.5 GHz. There is a big gap in or knowledge between these frequencies. This gap must be closed by surveys at 4.8 and 10 GHz that could be done by smaller radio telescopes. The polarization surveys of the Milky Way are improving after a long period of standstill. The polarization maps of nearby galaxies have reached an amazing level of perfection now that the addition of VLA and Effelsberg or Parkes and ATNF compact array data in polarization is possible. High resolution surveys at 325 MHz or at 1.4 GHz show considerable Faraday effects that in turn can be used to study foreground magnetic fields.

Pulsars and extragalactic radio sources are important probes of the Galactic magnetic field. We had several talks on this topic. Certainly first advances have been made but we are still a long way from probing the magnetic fields at a density that is appropriate to the magnetic field structure. We need 1000s of sources, well distributed on the sky before a significant analysis will be possible. The recent Hα surveys are a great help in the process of interpretation. In particular we need data on the Rotation Measure of more sources in the Galactic plane since this is where the magnetic fields are concentrated. Observers must be encouraged to make new observations.

The Zeeman results show us that this powerful method of measuring magnetic fields will become important one day in large-scale studies of Galactic magnetic fields. The number of sources observed in molecular clouds have now surpassed 100 but still needs a substantial increase to become really viable for Galactic scale interpretations. The various spectral lines probe different types of molecular clouds but it will be the large numbers of results that will improve the statistics and hence allow meaningful interpretation.

The radio sources that are showing us the action of magnetic fields, like supernova remants are an integral part of the investigations of the magnetic interstellar medium. Nearby galaxies, with their incredibly regular magnetic fields, pose a dilemma. Why do we not see more structure in the magnetic fields in nearby galaxies? Is this only a resolution effect? Is this due to a superposition of different emitting and Faraday rotating layers? Here the cry for an SKA becomes loud! Certainly the new simulations of magnetic fields show many observational-like features. We had no contribution about optical polarization observations, a pity. An important contribution that shows possible trends for the future described a polarization bolometer that can measure magnetic fields at sub-mm wavelengths. We need new instrumentation in radio and in sub-mm waves to come to new results.

One morning was devoted to the polarized Cosmic Microwave Background. We saw the wonderful WMAP results. We heard about the forthcoming PLANCK satellite project that will push the limits of our knowledge even further. The Boomerang and DASI experiments gave us the first results on cosmological polarization. Our community is busy preparing the "foreground correction". Both total intensity and polarized intensity of the Galaxy must be known exactly to allow to determine the cosmological contribution. Steps in this direction are well on the way. We had several theoretical contributions. Possibly too few, mainly due to passport problems of some intending participants.

Our Turkish hosts came to listen to the talks but also to present their work and their observatories. There are several world-class groups working in this country. The work is mainly theoretical, with good contacts world-wide. The dilemma of finding money for observatories is a stumbling block. In this day and age an astronomical facility that can contribute to world-class research is very costly. On the one hand a country needs training facilities. We had a talk about the TUBITAK National Observatory. Here a good level of performance has been reached that will ensure good training of future Turkish astronomers. On the radio astronomy side the picture was rather gloomy. Efforts to start mm observations and small-scale interferometry were described. These efforts need more support, especially on the engineering side. Radio astronomy is a subject that spans many disciplines: astronomy, physics and engineering. It is supported in many countries because of the technical innovations that it gives, also to the local industry. Possibly a better co-operation with technical universities is needed. Possibly some international (regional) venture could help to establish a viable radio observatory in this area. The Very Long Baseline Interferometry community is always eager to involve new observatories somewhere in the world to 'fill the visibility plane function'. There was some discussion about the virtual observatory concept. It is possible to get optical data or X-ray data from a data bank and use it. It is still rarely possible to get radio data in this way. There are several reasons for this. One reason is historical: radio astronomers did their own antenna construction, followed by receiver building, observations, data reduction and then finally interpretation. Many radio astronomers look at their data as their private possession. This situation I believe to be outmoded, but many of my colleagues still do it this way. Also radio data has many more parameters than optical or X-ray data. Calibration of radio observations still is a major effort often not understood by the casual user. Maybe the new large radio observatories like ALMA or SKA will provide the supporting staff to produce 'user friendly data'. I hope that the many bright students that we met during this conference will benefit from this one day.

My final words go to the organizers of the conference. Both Bülent Uyanıker and Aylin Yar-Uyanıker worked hard to get this conference organized from Bonn. They were ably supported by Wolfgang Reich and our great conference organizer Gabi Breuer. The local organization was supported by Prof. Z. Aslan and his group. We thank them all. The Sheraton Hotel staff, in particular Ms. Sema Alpaslan and her colleagues, must also be thanked for providing this beautiful and friendly venue. We leave Antalya with the hope that this week gave new impulses to many of us to continue to study our fascinating (radio) universe.