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Editors: R. Stone, K. Weiler, M. Goldstein, J-L. Bougeret
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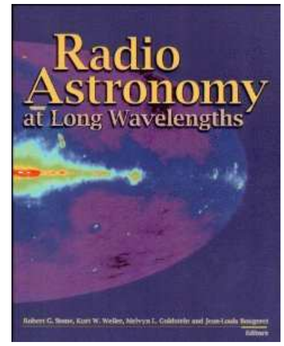
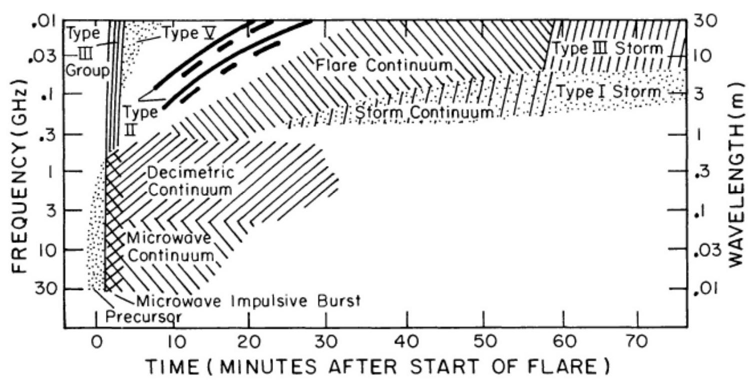
Reviewer: Whitham D. Reeve



For purposes of ***Radio Astronomy at Long Wavelengths***, the frequency range of interest spans from approximately a few kHz to around 100 MHz (wavelengths of 100 km down to 3 m). In radio engineering these are the VLF, LF, MF, HF and part of the VHF bands. Not all of this range is observable on Earth because its ionosphere blocks celestial emissions with frequencies below around 15 MHz (20 m wavelength). The actual cutoff frequencies are determined by solar activity and may be significantly higher or lower. It is for this reason that a considerable amount of long wavelength radio astronomy is undertaken from space, where the ionosphere cannot impair the observations. Another benefit of space-based radio observations is that the huge problem of manmade terrestrial radio frequency interference (RFI) is significantly reduced and at long wavelengths is completely eliminated by the ionospheric blocking.



There are many reasons to observe at long wavelengths, and many of those are nearby in our own solar system. They include the study of solar processes and space weather (image right from page 38 showing a schematic of solar radio emissions). Other radio sources are far away such as in the early universe. Their study includes cosmic evolution, the acceleration of relativistic particles, physics of the interstellar and intergalactic media and discovery (or "accidental") science – the search for and hopeful discovery of previously unknown sources and phenomena. It should not be surprising that these types of studies and observations are only possible through big science, big radio telescope arrays, big data storage, big signal processing and big money.

Radio Astronomy at Long Wavelengths is a collection papers from an American Geophysical Union conference in 1998. Each paper is really a summary of many other papers, which are listed as references. There is a lot of useful and interesting information here, something for everybody interested in the celestial radio environment below 100 MHz. Many of the papers and references are available for free download from the internet. The book is broken into five parts and each part has anywhere from a few to a dozen papers; the papers are well coordinated with very little overlap. The five parts of the book are *Generation of Radio Waves*, *Propagation and Scattering*, *Long Wavelength Radio Emission from the Solar System*, *Long Wavelength Radio Emission from Galactic and Extragalactic Sources*, and *Radio Telescopes for Long Wavelength Observations and Sounding*. The last part covers both terrestrial and space-based radio telescopes.

The breakdown of this book allows the reader to go right to the papers or areas of interest. The first two parts are good reviews and include **Planetary Radio Emission Mechanisms: A Tutorial**. There also are several papers on the various types of solar radio emissions. All papers are well illustrated with drawings, charts and images, many in color. The use of opaque mathematics is minimized but I occasionally got bogged down in terminology. Most authors assumed the reader is familiar with the jargon, but for me a glossary would have been helpful. I ended up reading the book from cover-to-cover over a time period spanning several months, but I was frequently interrupted while I searched for, downloaded and then read many of the excellent references.

There have been several terrestrial long wavelength radio observatories built (or under construction) since this book was written, including the Low Frequency Array (LOFAR), Square Kilometric Array (SKA), and Long Wavelength Array (LWA). These all are mentioned in the various papers and were in the planning stages at that time. The paper **The VLA at 74 MHz and Plans for the Long Wavelength Array** in the fifth part briefly discusses the Very Large Array in New Mexico, which was the site of the 2013 SARA Western Conference. Of great interest to me are the two LWA stations, one collocated with the VLA in New Mexico and the more recent station in California, the latter being the site of the 2014 SARA Western Conference. LOFAR and LWA also are discussed in **The Promise of Long Wavelength Radio Astronomy** in the fourth part. In 1998 the frequency ranges of LOFAR and LWA were to be equivalent. However, as it turned out, LOFAR is able to observe up to 240 MHz whereas the upper limit of the LWA is about 90 MHz. Both systems have RFI mitigation built into the system design, a first. It is noteworthy that neither system observes in the FM broadcast band because of the extreme difficulty of mitigating the interference from strong wideband FM broadcast signals.

The differences between LOFAR and LWA are not clear from the descriptions given in these papers; indeed, both have the same "science drivers" such as investigation of the re-ionization of the universe. This particular investigation probes the early universe by taking advantage of the high redshift of distant radio objects – the older the object, the higher the redshift and the lower the frequency of radio emissions. Other science to be undertaken includes the first radio galaxies and black holes in the very young universe, high energy phenomena, and others. It is seen that the broad plans for a radio telescope require considerable time to implement. However, one of the important facets of radio astronomy is that once the infrastructure is in-place, new technology can be used to extend and expand its usefulness. In fact, new technologies enable new discoveries.

I was slightly surprised this book makes no mention of the possible effects of terrestrial phenomena such as earthquakes and volcanoes on low frequency radio propagation. No such activity is mentioned in ***Radio Astronomy at Long Wavelengths***, perhaps because these phenomena did not fall under the definition of radio astronomy. On the other hand, we have the well-publicized concerns about bad space weather causing massive communications and power systems disruptions and disturbing our comfortable lives. About 25% of the book (over 100 pages) is dedicated to radio emissions in our solar system. The Sun is easily the most powerful nearby radio source. By studying solar radio we hope to better understand how the Sun works. This knowledge presumably would then be used to build more robust power and communications infrastructure.

On the less disruptive side are the studies of planetary radio emissions and the radio and magnetic effects of the many moons. Studies such as these are supposed to help fill the wide gaps in our knowledge of how the planets, including Earth, formed and evolved. The part *Long Wavelength Radio Emission from the Solar System* includes a section dedicated to the planets. It starts out with a concise but informative paper **Radio Emissions from the Planets and Their Moons**. We learn that by 1998 nine types of radio components were known to originate from the magnetospheres of the five strongly magnetized planets – Earth, Jupiter, Saturn, Uranus and Neptune. The nine components are thermal, from Van Allen belts, lightning, auroral, satellite induced, equatorial, bursts, narrowband kilometer radio emission and non-thermal continuum. A table in this paper neatly summarizes the radio components, planet from which they have been detected, wavelength and basic radiation process.

None of the planets emit all radio components, but Jupiter, with its very strong magnetic field and huge magnetosphere produces at least eight. Jupiter's magnetic characteristics enable emissions above around 15 MHz allowing them to be detectable on Earth's surface. The non-thermal emissions from all other planets are at lower frequencies and blocked by Earth's ionosphere from terrestrial detection. Their existence was not confirmed until spacecraft detected them. The hot, dense and enigmatic planet Mercury is thought to produce non-thermal radio emissions, too, but it has such a tiny magnetosphere that the emissions likely are trapped by it and would require a very close fly-by to detect. The Messenger Spacecraft explorations starting in 2008 through the present were not designed to detect radio emissions, so we will have to wait until the European-Japanese BepiColombo mission arrives at Mercury in 2023.

Another paper in the planetary section, **SL9: The Impact of Comet Shoemaker-Levy 9 at Jupiter**, concerns the radio effects of the comet collision with Jupiter in July 1994. Many radio telescopes on Earth and on spacecraft observed Jupiter before, during and after the event. Both short-term and long-term radio flux density changes were observed at frequencies above around 300 MHz. However, no effects were observed in the HF band from the radio sources familiar to Radio Jove observers. As stated "no significant change from the usual level of Jovian decametric activity was observed that could confidently be attributed to the comet impacts." This paper contradicts the vehement claims by a group of amateur radio astronomers at that time. In addition, no effects were observed at kilometer wavelengths (10s and 100s of kHz).

Some important investigations described in this book include the origin of cosmic rays and long wavelength observations of Supernova Remnants. These are discussed in the fourth part, which starts out with **Long Wavelength Astrophysics**, a review of radio emissions not discussed in previous sections. This is where the reader finds a description of synchrotron emission, steep spectra, Faraday rotation, spectral turnovers (reversal of the spectral index) and coherent emission. These descriptions are brief but all are given in the context of long wavelength radio astronomy and may be pursued through the references given. Additional papers in this part discuss Moon-based radio telescopes, problems with RFI and what the sky would look like at long wavelengths. The latter is a survey of existing long wavelength sky maps and measurements and includes speculation as to what may be seen with additional investigations from Earth and from space. Pioneer radio astronomer Grote Reber's sky map at 2.1 MHz (144 m wavelength) is included here from a paper he wrote in 1968.

The final part of ***Radio Astronomy at Long Wavelengths*** gives an overview of radio telescopes that are used at long wavelengths. Most of these are probably familiar to contemporary amateur radio astronomers. Covered here are the Giant Metrewave Radio Telescope (GMRT) consisting of thirty 45 m diameter dish antennas in western India, the UTR-2 (Ukraine T-shaped Radio telescope) with a frequency range of 8 to 40 MHz, and the Nancay Decameter Array that operates in the 10 to 80 MHz range in France, among others. One of the last papers in this part is *Lunar Surface Arrays*, heretofore unbuilt projects studied by NASA in the 1990s and interesting to read and speculate about.

In conclusion, ***Radio Astronomy at Long Wavelengths*** is not a cheap book but it covers many topics of interest and covers frequencies easily accessible to amateur radio astronomers. Although at the time it covered the subject very well, some of the material on future radio telescopes is obviously incomplete compared to what is available now. However, the discoveries up to 1998 are well-covered and referenced, allowing interested readers to obtain additional details.

Reviewer - Whitham Reeve is a director of SARA and is contributing editor for the SARA journal, *Radio Astronomy*. He worked as an engineer and engineering firm owner/operator in the airline and telecommunications industries for more than 40 years and has lived in Anchorage, Alaska his entire life.