RADIO POLLUTION OF THE OH 1612-MHZ BAND

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ABSTRACT. The hydroxyl radical (OH) was the first interstellar molecule to be detected by radio telescopes and its spectral lines at 1.6 GHz have good regulatory protection. Despite this, astronomical research using the 1612-MHz line of OH is now compromised by interference from satellites which transmit on nearby frequencies. The nature of the science which can be done only at 1612 MHz is reviewed and the effects of interference from GLONASS are explained. The effects of the interference can be mitigated in some circumstances, with an associated loss in observing time or sensitivity. Attention is drawn to the large number of similar interference problems which could be caused by new generations of satellites, including Iridium.

1. Introduction

Radio astronomy is a young branch of astronomy, but one which has completely transformed our view of the Universe. The radio window is the only waveband apart from the optical which is accessible to ground-based instruments. The opening of this window gave us our first glimpse of phenomena which had been largely hidden to optical telescopes. The discovery of interstellar molecules, of pulsars, masers, radio galaxies, quasars and the cosmic microwave background radiation were all made during the pioneering days of radio astronomy. These discoveries were followed by revolutions in radio imaging, and by steady improvements in angular resolution and sensitivity (Kellerman 1997), which have allowed us to probe ever deeper into the universe. The technique of very-long-baseline interferometry (VLBI) offers the highest angular resolution which can be achieved in any branch of astronomy (now measured in microarcseconds). Yet now radio astronomy finds itself under threat from new technology on satellites.

Cosmic radio sources produce power levels at the Earth's surface which are extremely low and are easily masked by manmade signals (Thompson et al. 1991). Transmitters on satellites pose a particularly serious threat to radio astronomy because they lie in direct line-of sight of the radio telescope. Under these conditions not only intentional transmissions but also unwanted emissions can cause interference. Modern satellites employ techniques of wide-band digital modulation and beam-forming by active antennas which inevitably lead to unwanted emissions. When such satellites operate close to a frequency band used by radio astronomy then interference is almost inevitable. This paper describes interference from satellites into the radio astronomy band 1610.6–1613.8 MHz, which is used primarily for observations of the 1612.2-MHz spectral line of the hydroxyl (OH) radical. The problems encountered there are a warning of what may lie ahead in many other radio astronomy frequency bands.

2. Astronomy at 1612 MHz

OH 1612-MHz emission is characteristic of a special class of astronomical objects, the OH-IR sources. OH-IR sources are red giant stars which have evolved beyond the asymptotic giant branch and are losing mass at prodigious rates of up to 10^{-4} $M_{\odot}yr^{-1}$ (Habing 1996). The stars are usually long-period variables with periods of 1 to 6 years. The thick shell of circumstellar matter absorbs most of the starlight, which is re-emitted as infrared radiation, hence the name OH-IR sources. OH-IR sources are of great interest for theories of stellar evolution, and as a source of nuclear-processed material for the interstellar medium. Our Sun will one day pass through this phase, on its way to becoming a planetary nebula. About three thousand OH-IR sources are now known, as a result of 1612-MHz surveys of IRAS-selected targets and systematic surveys of the galactic plane and the galactic bulge.

Without the OH 1612-MHz line we would know very little about OH-IR sources. The 1612-MHz line is excited as a maser in the outer layers of the circumstellar envelope by an infrared pump, details of which have recently been confirmed by *ISO* (Sylvester et al. 1997). The shell of 1612-MHz maser emission can be directly observed using radio interferometers such as MERLIN (Booth et al. 1981). The angular sizes are typically one second of arc or less. The maser emission varies in synchronism with the varying infrared pump, but because of the light travel time across the shell we see a phase-lag between the blue-shifted and red-shifted emission. Measurement of this phase-lag together with an interferometer measurement of the OH shell diameter thus yields the distance to the star. This powerful technique is now being used at several radio observatories around the world. Regular monitoring over many years is required.

A typical 1612-MHz spectrum of an OH-IR source is shown in Figure 1. The spectrum is usually twin-peaked like this because the maser emission is beamed radially outwards from the star. We therefore see strongest emission from the very front and the very back of the OH shell. The stellar velocity is accurately defined by the midpoint of the two 1612-MHz peaks, and the separation between the two peaks gives twice the expansion velocity of the shell. Expansion proper motions have been directly measured using VLBI (Kemball 1992). The lower half of Figure 1 shows that the 1612-MHz emission is polarized. Linear and circular polarization have both been measured. Polarization imaging yields information on the circumstellar magnetic field (Szymczak & Cohen 1997).

OH-IR sources are one of the few stellar populations whose distribution and kinematics can be studied throughout the Galaxy. Lindqvist et al. (1992a, 1992b) have surveyed the galactic centre for OH-IR sources and determined accurate positions and radial velocities. Treating the OH-IR sources as test particles in the galactic potential they were able to deduce the existence of a central concentration of mass, possibly a 2×10^{6} $M_{\odot}$ black hole.

Apart from the study of OH-IR sources, the 1612-MHz band is used for many other purposes. The 1612-MHz line is one of 4 transitions of OH in its rotational ground-state, and observations of the different line ratios are an essential diagnostic of the physical conditions in the molecular gas. The 1612-MHz line is studied in a wide range of objects including comets, star-forming regions, molecular clouds and outflows, and in external galaxies (where the red-shift may take the line out of the allocated band). Powerful OH

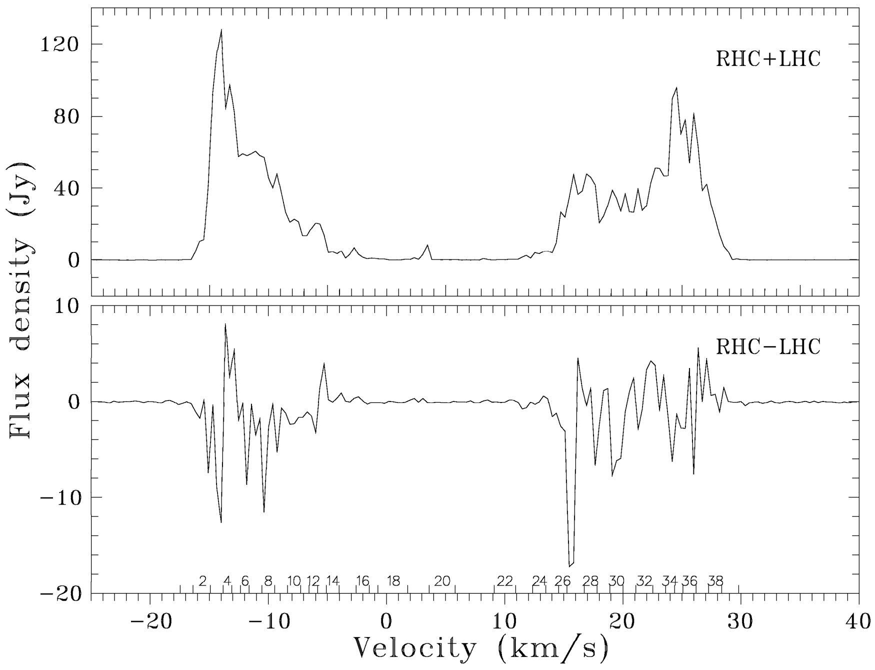

Fig. 1. OH 1612-MHz spectrum of VXSgr, taken with MERLIN on 23rd October 1993 and covering a bandwidth of 360 kHz with a resolution of 2 kHz (Syzmczak & Cohen 1997).

megamasers are perhaps the most spectacular objects observed at 1612-MHz.

Continuum observations are also made at 1612 MHz for various purposes. Nevertheless in what follows the effects of interference will be discussed only for the spectral line measurements for which the radio astronomy band is primarily intended.

3. Interference from GLONASS

The Russian global navigation satellite system GLONASS has caused worldwide interference to radio astronomy at 1612 MHz since it was first launched in 1982 (Ponsonby 1991). GLONASS uses a constellation of satellites in three orbital planes, with 8 orbital positions per plane. The orbital period is such that after 24 hours each satellite has completed exactly two and one-eighth orbits. The GLONASS satellites transmit one of their main navigation signals on 25 possible centre frequencies equally spaced from 1602.0 to 1615.5 MHz. Six of the frequency channels fall directly in the radio astronomy band 1610.6–1613.8 MHz.

The peak power flux density produced at the Earth's surface by a single GLONASS satellite is about -190 $\mathrm{dBWm^{-2}Hz^{-1}}$, or in radio astronomical units 10^7 Jy. For comparison the known OH-IR sources have peak flux densities ranging from a few hundred Jy down to a few mJy. A 70-m class radio telescope with a gain of 60 dBi at 1612 MHz will still collect signals from GLONASS through its far sidelobes. A GLONASS satellite in a 0 dBi sidelobe will appear as strong as a 10 Jy source in the main beam. The situation will be even worse for a smaller radio telescope with less gain in the main beam. Consequently GLONASS satellites with centre frequencies in the radio astronomy band are able to cause interference whenever they are above the horizon, not just when a radio telescope is pointing near them.

The GLONASS navigation signal is phase-modulated with two codes, a low precision code which is switched at 0.511 MHz, and a high precision code which is switched at 5.11 MHz. The switching is abrupt, and generates sinc-squared sidebands at both frequency intervals. These unwanted emissions, which are not needed by the navigation receiver, spread over many hundreds of MHz. Additionally narrow emission spikes, rather like OH masers, are generated at each 5.11 MHz, at the nulls in the sinc-squared pattern. The power levels are such that the unwanted emissions from GLONASS are capable of causing interference in the adjacent radio astronomy band 1660–1670 MHz (Galt 1990) and indeed over hundreds of MHz.

The effects of GLONASS vary for different telescopes and for different types of radio astronomical measurement. For spectral line measurments at 1612 MHz the effects can be broadly classified into spectral artefacts and calibration errors. Spectral artefacts from GLONASS reflect the spectrum of the transmitted signal, and may be narrow band, from the null spikes, or wide band from the sinc-squared sidebands. If position-switching or frequency-switching are employed in the measurements the artefacts are due to the difference in received GLONASS energy in the ON and OFF spectra, rather than the absolute energy received. Calibration errors occur because of the rapidly varying power levels received from GLONASS satellites as they move through the sidelobe pattern of the radio telescope. Unless the calibration signal, usually from a noise diode, is sampled rapidly, systematic errors will be introduced because of the unknown contribution of GLONASS to the noise power at the detector.

4. The GLONASS-Radio Astronomy Experiment

The impact of GLONASS on radio astronomy at 1612 MHz was devestating. Astronomers were dismayed at how quickly and simply a whole area of research could be wiped out by a small number of satellites. The worldwide nature of the problem meant that a global solution had to be found. A series of meetings was set up between the GLONASS Administration and IUCAF, the Inter-Union Commission on Frequency Allocations for Radio Astronomy and Space Research. From these talks came a proposal for a joint experiment to test several ways of reducing the interference to radio astronomy.

The joint experiment took place on 19th-22nd November 1992, with 10 radio astronomy observatories in 8 countries participating. During the three-day period GLONASS satellites were moved in frequency and in some case switched off altogether, so that the effects on the radio astronomy measurements could be investigated (Cohen 1994). The measurements included single telescope spectroscopy, interferometry, and total power (continuum) measurements. In addition the power spectrum of each satellite was monitored at the German Monitoring Station in Leeheim. Knowing the orbits of the satellites and the centre frequencies of their transmissions it was possible to learn exactly how signals from different satellites were entering the radio astronomy receiver and what effect they were having on the measurements.

The outcome of the experiment was an agreement between GLONASS and IUCAF, signed on 4th November 1993. The agreement set out a step-by-step plan to reduce interference to radio astronomy. In the first stage the main transmissions of the low precision code were excluded from the radio astronomy band 1610.6–1613.8 MHz. This was already done in 1993, which immediately lowered the interference levels by an order of magnitude. By 1999 the main transmissions of the high precison code will also be excluded, which will bring a further order of magnitude improvement for radio astronomy. This is being achieved by reusing frequency channels for satellites on opposite sides of the same orbit, so that only 13 channels are occupied, not 25. Meanwhile new-generation GLONASS-M spacecraft are being developed which will carry filters to reduce the unwanted emissions at 1660–1670 MHz below the threshold for interference. The new satellites will operate at lower frequencies with a modified frequency plan, and are expected to be fully in place by the year 2006 (a deadline which is not in the original agreement but which was subsequently adopted).

The step-by-step plan has brought immediate benefits to radio astronomy. It allows useful measurements to be made on strong sources right now, and there is the long-term prospect of a clear 1612-MHz band by the year 2006. Nevertheless prevention would have been better than cure. How did the system fail radio astronomy?

5. Regulatory Matters

The use of radio frequencies is regulated by the Radiocommunications Bureau of the International Telecommunications Union (ITU-R). The rules or Radio Regulations are agreed internationally at World Radio Conferences (WRCs, formerly WARCs). Radio astronomy first entered the Radio Regulations in 1959 when a passive frequency band was allocated to protect the 1420-MHz line of atomic hydrogen. The four OH lines at 1.6 GHz were recognized in 1971 when they were given shared allocations, not passive bands. Shared allocations are common in the table of frequency allocations, reflecting the pressures on the radio spectrum. At the time of the GLONASS launch the OH 1612-MHz band was shared with, among others, the radio navigation service. The launch of GLONASS was officially notified and national administrations had the opportunity to object, but almost nobody realized what was about to happen to radio astronomy at 1612 MHz.

The Radio Regulations contain no penalties for causing interference. Radio astronomy does not have a strong regulatory position within the Radio Regulations in any case, as the protection criteria, which are given in Recommendation RA.769-1 of the ITU-R, have never been made mandatory. It took the growing swell of international unrest about GLONASS, and other political factors within the USSR and elsewhere, to bring the negotiations about.

In order to ensure that there is no repeat of the GLONASS situation the interference levels for radio astronomy will need to be written into the Radio Regulations as mandatory levels, not just recommended levels. In addition the levels of unwanted emissions from transmitters on satellites will need to be tightly specified. At present there are no limits at all! The telecommunications community has shown no wish to constrain itself in these ways, so the pressure will need to come from governments. Reduced levels of radio pollution will benefit all users of the radio spectrum, not just radio astronomers.

6. Interference Mitigation

In response to GLONASS interference radio astronomers have developed mitigation techniques which may stand them in good stead in the future and at other frequencies.

ITU-R RA.769-1 specifies a threshold of -238 dBWm^{-2}Hz^{-1} for interference detrimental to radio astronomy spectral line measurements at 1612 MHz. The calculation used to derive this threshold assumes values for the receiver noise temperature (20 K), integration time (2000 s) and resolution bandwidth (20 kHz). It further assumes that the interfering signal enters through sidelobes of gain 0 dBi. Under these assumptions a steady interfering signal at the detrimental threshold adds noise fluctuations σ_h to the measurements which are less than ten percent of those due to receiver noise σ_n. GLONASS levels in the band 1610.6–1613.8 MHz are currently almost 40 dB above the threshold for detrimental interference. How is science possible under these conditions?

Firstly radio astronomers take precautions to minimize interference from GLONASS, for example by observing when certain satellites are below the horizon, and by careful editing and processing of corrupted data (Combrink et al. 1996). Analysis of data recorded at Jodrell Bank during the GLONASS experiment indicates that most of the GLONASS signal in a 1200-s integration entered the receiver during a relatively short period of time. It is thus possible to improve the data quality considerably by taking many short integrations and discarding those which are worst affected by interference. Spectral artefacts from GLONASS have known characteristics, which aids in their identification. Observations of narrow-band OH sources are worst affected by the null spikes, which mimic narrow maser features, but they are at known frequencies. The broad-band sinc-squared components can be removed to some extent by fitting polynomial baselines to the spectra.

With the above measures most large radio telescopes can make useful observations of strong narrow-band sources, such as the strongest OH-IR sources. On the other hand it is impossible at the present time for such a telescope to make useful measurements of weak sources or of broad-band sources such as OH megamasers and bipolar outflows like OH231.8. These and other research areas requiring the highest sensitivity are on hold until the year 2006 when the GLONASS step-by-step plan is completed.

Interferometers are less susceptible to interference than single telescopes. The MERLIN spectrum of Figure 1 is only weakly contaminated by GLONASS, at a level 25 dB lower than would be the case for a single telescope. In fact the GLONASS terms are at a similar level to the receiver noise σ_n in a spectral channel (0.02 Jy), and useful science can be done. An equivalent integration with a single telescope would have artefacts of $300 \times \sigma_n$ and would be useless. Interferometers are increasingly being used at 1612 MHz for searches and other high sensitivity programmes. However interferometers offer only a partial solution. They are few in number compared with single telescopes, and they are suitable only for compact sources, not for extended sources.

7. Iridium

At WARC-92 the allocation of the band 1610.6–1613.8 MHz to radio astronomy was upgraded to primary status. At the same time the band 1610–1626.5 MHz was allocated to the mobile satellite service to allow the introduction of a new generation of communications satellites in low Earth orbits (LEOs). All of the proposed systems will use the band 1610–1626.5 MHz for uplink transmissions. In addition one system, Iridium, will operate its downlink within this band. Iridium is the first to fly and will begin commercial operations later this year (1998).

Iridium employs a constellation of 66 satellites in low Earth orbit to provide mobile communications between any two points on the planet. The Iridium downlink will operate in the band 1621.35–1626.5 MHz initially, although the satellites are capable of transmitting down to 1616 MHz and the allocation extends down to 1613.8 MHz. The downlink is for reception by small handheld units and it has a peak spectral power flux density of -160 $\mathrm{dBWm^{-2}Hz^{-1}}$ or 10^{10} Jy, one thousand times GLONASS. For this and for other reasons concerning the antenna beam-forming system the technical challenge to suppress unwanted emissions into the radio astronomy band is greater than for GLONASS. The Iridium downlink was identified as a potential threat to radio astronomy as early as 1991. To safeguard against interference a footnote was modified at WARC-92, at the same time as the allocation for the satellite downlink was made. Footnote S5.372 states that harmful interference shall not be caused to stations of the radio astronomy service using the band 1610.6–1613.8 MHz by stations of the radiodetermination-satellite and mobile-satellite services.

Negotiations between Iridium and the radio astronomy community have been proceeding since 1991. At a certain point it became clear that the Iridium downlink might fail to meet the thresholds for detrimental interference to radio astronomy. The unwanted emissions from Iridium satellites increase with user traffic, and Iridium's own calculations suggested that the fully loaded system could exceed radio astronomy interference thresholds by up to 27 dB. At this point Iridium began to call into question the radio astronomy protection criteria and the interpretation of the Radio Regulations, and some of the negotiations foundered (Feder 1996).

Iridium has declined to discuss the issues globally with IUCAF, as the GLONASS administration did, but has made some progress in discussions with individual observatories. Radio astronomers in the USA have accepted a time-sharing solution in which radio astronomy to the levels of ITU-R RA.769-1 will be guaranteed only during the quiet hours when the phone traffic is low. Radio astronomers outside the USA have so far resisted the pressures to sign similar time-sharing agreements.

8. Future Prospects

The difficulties in doing radio astronomy at 1612 MHz seems as if they may get worse before they get better. Nor is this an isolated problem. The number of cases of interference to radio astronomy from satellites is steadily increasing. An updated list can be inspected on the home page of the European Science Foundation's Committee on Radio Astronomy Frequencies ESF-CRAF (http://www.nfra.nl/craf). In fact 80% of frequency bands with a primary worldwide allocation to radio astronomy are adjacent to satellite downlink bands, and could present similar problems in future. This constitutes a major challenge to the future of radio astronomy. Fortunately most of the downlink allocations have not been taken up yet, so there is time to improve the technology on satellite transmitters and on radio telescopes and receiver systems.

As the millenium approaches the ITU-R itself is undergoing many changes. The radio spectrum has become a valuable commodity. Global corporations can make billions of dollars per Megahertz, and they are able to exert enormous pressure on national administrations and through them on the ITU-R. Millions of dollars are spent at WRCs on food, drink, parties and free gifts for delegates. Many multinational operators are on national delegations both to WRCs and to smaller ITU-R working groups. At the same time adminstrations are seeking to minimize their own role in managing the use of the radio spectrum.

The negotiations with Iridium have brought radio astronomers face to face with the world of corporate lawyers, non-disclosure agreements, commercial confidentiality and industrial espionage. It is an extreme clash of cultures. In this arena radio astronomers need to find new ways to achieve their goals.

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