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# New radio instrumentation for the study of sunspots and starspots

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**Abstract.** Much of the radio emission from the Sun and similar stars depends directly on magnetic fields for its source. For this reason, radio emission contains important diagnostic information on solar and stellar magnetic fields. This paper reviews the ways in which radio emission is sensitive to magnetic fields and discusses new radio instrumentation that will be able to exploit this information for major advances.

**Key words:**

## 1. Introduction

Radio observations provide a unique perspective for the study of coronal magnetic fields. They are directly sensitive to magnetic field strengths and allow us to observe coronal magnetic fields projected against the solar disk. Photospheric and chromospheric field strengths can be measured with optical and infrared lines, but presently no magnetically sensitive coronal lines have been identified that can be used to measure coronal magnetic fields against the bright solar disk. Such fields can easily be measured at radio wavelengths using gyroresonance emission. In this review we discuss how radio observations are sensitive to coronal magnetic fields, and then discuss planned radio projects that will enhance our ability to study them.

Figure 1 contrasts the appearance of the Sun at radio wavelengths with other common wavelengths (EUV and optical). While there is considerable similarity between the radio and EUV images, as expected since both show emission from hot coronal plasma (Fe XII line emission in the EUV image, bremsstrahlung continuum in the radio image), the brightest radio features have no counterparts in the EUV image: rather, the optical image shows that they are associated with sunspots. Figure 2 shows the same result in more detail: as one goes from low to high frequencies the radio image ceases to be dominated by bremsstrahlung from the hot soft X-ray-emitting loops and instead shows the locations of strong magnetic fields in the corona. The next section describes how the magnetic fields produce these radio sources.

## 2. Radio emission from coronal magnetic fields

Radio observations measure coronal magnetic field strengths using gyroresonance emission. They can presently be used for field strengths in excess of several hundred Gauss. The mechanism involves a resonance between electromagnetic waves and electrons spiralling along magnetic field lines at the electron gyrofrequency, $f_B = 2.80 \times 10^6\, B$ Hz, where $B$ is measured in G. This resonance produces strong coupling between electrons and radiation at low harmonics of the electron gyrofrequency ($f = sf_B$ where $s$ = 1, 2, 3, 4). The properties of the mechanism are very well understood (e.g., Zlotnik 1968; White & Kundu 1997): (i) The two natural electromagnetic modes of the plasma are circularly polarized under most conditions: the $x$ mode, which rotates in the same sense as the electron gyrates about the field, interacts more strongly than the $o$ mode which has the opposite sense of rotation. The $o$ mode opacity is always at least an order of magnitude smaller than the $x$ mode opacity. (ii) The gyroresonance opacity at harmonic $s$ is $\propto \; N_e\,(s^2 \sin^2\theta\, T_e/m_e c^2)^{s-1}$, where $\theta$ is the angle between the line of sight and the magnetic field direction in the source, $N_e$ the electron density and $T_e$ is the temperature. The opacity drops sharply towards small $\theta$ (**B** parallel to the line of sight) in both modes. (iii) For typical coronal conditions, the $x$ mode is optically thick ($\tau \geq 1$) in the $s$ = 2 and 3 layers over a broad range of viewing angles $\theta$. The $o$ mode is optically thick over most of the $s$ = 2 layer, and may be at least marginally optically thick over a small portion of the $s$ = 3 layer where $\theta$ is close to 90°. Harmonics greater than $s$ = 4 do not have any significant optical depth in the quiet solar corona, although there

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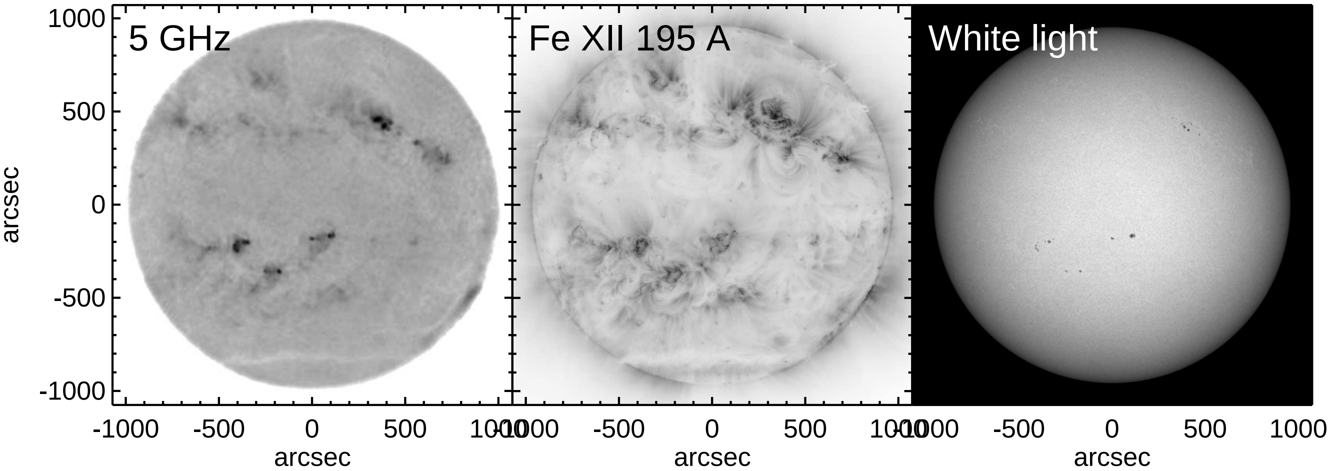

**Fig. 1.** A comparison of the appearance of the Sun at radio wavelengths (left, VLA mosaic image at 5 GHz) with EUV wavelengths (middle image, SOHO/EIT 195 Å Fe XII image) and optical continuum (right panel, SOHO/MDI continuum). These images were obtained on 1999 April 11. In the radio and EUV images the color table is inverted so bright features appear dark.

may be $x$ mode emission from the 4th harmonic if the temperature is high (Lee et al. 1997). (iv) For each increase of $s$ by 1, the opacity in a given mode at a given angle drops by more than 2 orders of magnitude. This is largely due to the $(T_e/mc^2)^s$ dependence of the opacity. The importance of this large change in opacity from one layer to the next is that a given harmonic layer is likely to be either optically thick over a wide range of angles $\theta$, or else optically thin everywhere. Density has much less influence on the opacity than the harmonic number. (v) The thermal width of the cyclotron resonance at coronal temperatures is such that $B$ typically varies by less than 2% across a resonant layer. corresponding to a physical width of less than 200 km for typical coronal magnetic gradients (scale length $\sim 10^4$ km). (vi) The narrow physical thickness of the gyroresonant layers is an important feature of this mechanism: since they are much smaller than relevant gradients in $N_e,\ B$ and $T_e$ (except possibly in the vicinity of current sheets), these physical properties may be regarded as constant across any given gyroresonant layer.

These properties are illustrated in Figure 3, which shows the radio emission from a simple sunspot observed almost directly from above with the VLA on 1994 October 15. Because radio wavelengths are in the Rayleigh–Jeans limit (i.e., well to the long wavelength side of the thermal peak in the electromagnetic spectrum), the radio brightness temperature on the sky is proportional to the temperature of the source: $T_B = (1 - e^{-\tau})T_e$, where $\tau$ is the optical depth through the source. In particular, wherever the atmosphere is optically thick to radio emission, the observed radio brightness temperature is the actual temperature of the electrons which produce the emission. This fact provides a useful tool: any feature which is observed to have a coronal brightness temperature is therefore optically thick. Bremsstrahlung from the hot dense plasma in loops above active regions is optically thick only at the lower radio frequencies (below 3 GHz). Due to its $f^{-2}$ dependence, the optical depth of bremsstrahlung drops rapidly as frequency increases, so the identification of features at coronal temperatures at radio frequencies above 3 GHz as gyroresonance sources is generally unambiguous. A technique which exploits both gyroresonance and bremsstrahlung emission to derive the magnetic field, using EUV data to “remove” the bremsstrahlung contribution, has been developed by Brosius et al. (1997).

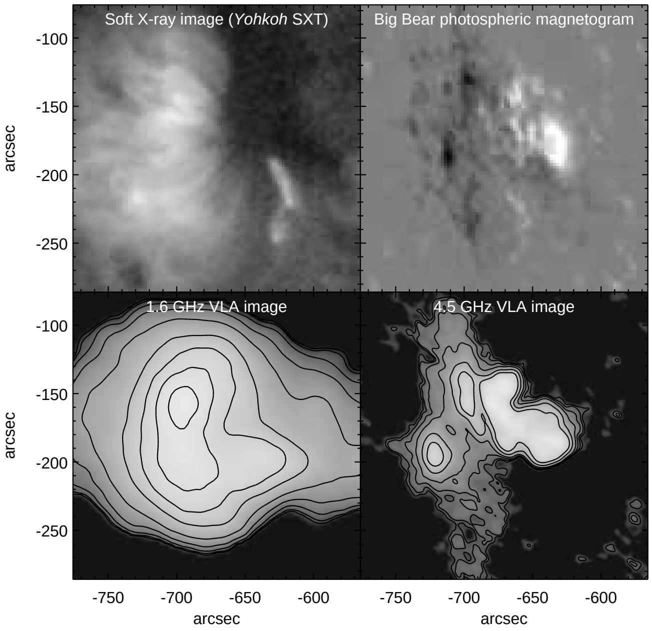

**Fig. 2.** Contrast in the appearance of a solar active region (1992 April 11). A soft X-ray image (Yohkoh/SXT) is shown in the top left panel, a longitudinal magnetogram in the top right panel, and two VLA radio images are shown in the lower panels: a 1.6 GHz image at left, and a 4.5 GHz image at right. Note the striking difference in the radio images: at the lower frequency the radio image is dominated by optically-thick bremsstrahlung from the loops visible in the soft X-ray image. At the higher frequency this emission is optically thin, and the image is dominated instead by gyroresonance emission from the strong magnetic fields in the corona above the active region.

When “decoding” observations of gyroresonance emission in terms of coronal magnetic fields, we can regard any source above 3 GHz that has a coronal brightness tempera-

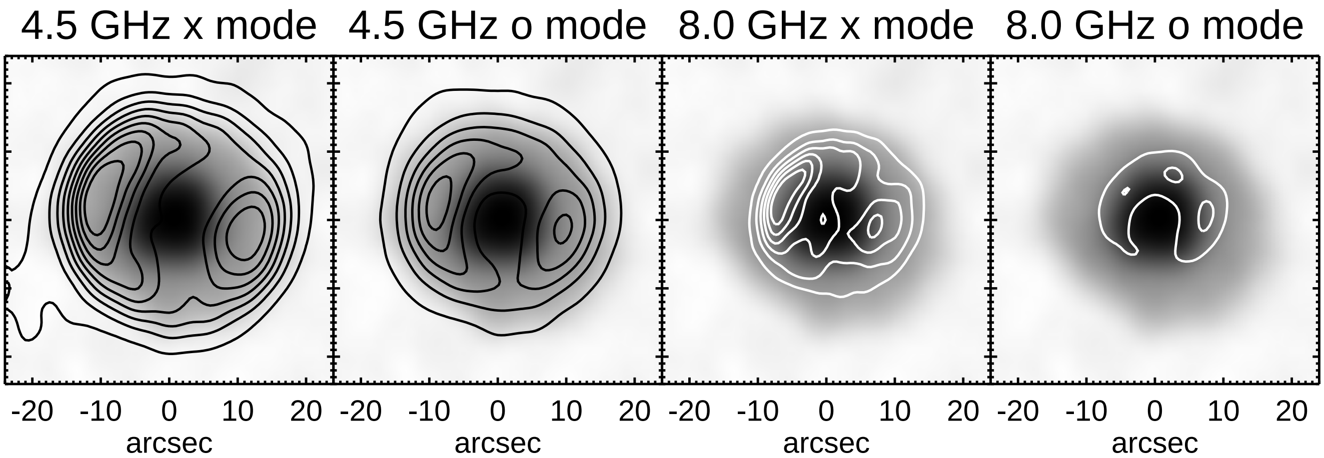

**Fig. 3.** Radio contours (at two frequencies in each of two polarizations) plotted over a white light image of a sunspot for a particularly simple spot observed close to disk center with the Very Large Array on 1994 October 15. Contours are plotted at brightness temperatures of 1, 3, 5, 7, ... $\times\ 10^5$ K. As noted in the text, 4.5 GHz corresponds to a magnetic field strength of 540 G if emission is at $s$ = 3, while 8.0 GHz corresponds to 950 G. The radio emission is low over the center of the spot where we are looking nearly parallel to the magnetic field direction in the corona and the opacity is low, whereas at the outer edge of the spot the opacity is high because $\theta$ is larger and optically thick radio emission at coronal temperatures is observed.

ture or a high degree of circular polarization as a gyroresonance source. It is helpful to think in terms of the surfaces of constant magnetic field strength ("isogauss") above an active region. At a given frequency $f$, gyroresonance opacity is only significant in the isogauss layers along the line of sight at which $f_B$ = $f/s$, $s$ = 1,2,3,... When we look down on an active region from above, we see down to the highest isogauss layer which is optically thick in the corona. This will generally be the $s\ =\ 3$ layer in the sense of circular polarization corresponding to the $x$ mode and the $s\ =\ 2$ layer in the $o$ mode, e.g., the 600 G layer in the $x$ mode and 900 G in the $o$ mode at 5 GHz. For a region on the disk, $\theta$, and therefore opacity, will be largest at the outer boundary of an isogauss layer: thus the outer boundary of the optically thick radio source should indicate where the isogauss surface drops below the corona into the chromosphere. This property allows us straightforwardly to measure the magnetic field strength at the base of the corona. An example of this technique is shown in Figure 4, which shows a true coronal magnetogram. An important point is that gyroresonance observations are sensitive to the absolute magnetic field strength $B$, whereas conventional (Babcock or Leighton style) optical magnetographs measure only the line–of–sight component of the magnetic field, $B\cos\theta$, and thus are of limited value for regions near the solar limb.

While optically thick emission is usually regarded as a disadvantage for diagnostic purposes, because it prevents us from seeing material under the optically thick layer, it is actually an advantage when studying coronal magnetic fields. In the Sun's atmosphere different radio wavelengths are optically thick at different heights and thus all layers can be studied by making images at many frequencies across a broad frequency range. This gives us the three–dimensional information necessary to study the coronal field, whereas an optically thin diagnostic necessarily integrates over all emission along the line of sight and no discrimination for depth is possible.

## 3. Properties of Coronal Magnetic Field Strengths

A common argument applied to coronal magnetic field strengths is as follows: magnetic flux in the (high–$\beta$) solar photosphere tends to be concentrated in small regions of intense (kG) field strength. As this flux rises into the low–$\beta$ solar corona it will expand laterally, thus diminishing the strength of the field. This argument is the basis for the wide–spread belief that coronal magnetic fields are much weaker than the fields measured in the photosphere. The argument appears to be valid for the quiet–Sun fields concentrated in small flux tubes in the cell network: if these fields reached the solar corona with strengths of order of hundreds of G or more, we would see clear signatures in radio images of the Sun in the form of features over the network at coronal temperatures. Such signatures are not seen (e.g., Gary et al. 1990). However, present upper limits for magnetic field strengths in the corona above quiet–Sun regions are well above the field strengths expected from the flux expansion argument.

On the other hand, the argument does not apply to active regions fields. Field strengths of 2000 G or more can be found in the corona, particularly over large sunspots (Shibasaki et al. 1994): in active regions there is so much flux that there is little field–free volume to expand into, and so field strength declines much less rapidly with height than simple models tend to predict (Akhmedov et al. 1982). For example, in Figure 4 the maximum line–of–sight field in the photosphere is not much more than 2000 G, yet coronal fields of 1800 G are found to be present. The recent coronal line measurements above active regions at the limb agree with this conclusion (Lin et al. 2000), as does the fact that loop width measurements find that coronal loops tend to have constant widths, rather than showing expansion at greater heights (McClymont & Mikić 1994, Klimchuk 2000).

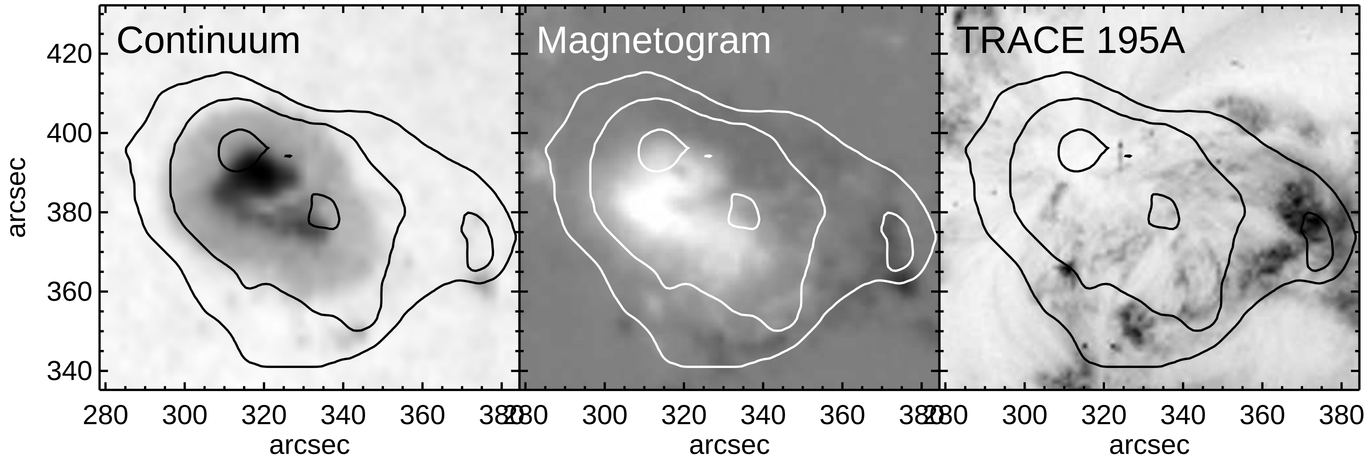

**Fig. 4.** Contours of magnetic field strength at the base of the corona plotted on white light (left), magnetogram (middle) and TRACE 195 Å Fe XII (right) images of a sunspot observed on 1999 May 13. The coronal contours are plotted at 500, 900 and 1700 G, corresponding to the radio images at 4.5, 8.0 and 15.0 GHz used to construct the coronal magnetogram. Note the displacement of the 1700 G coronal magnetic field strength from the strongest photospheric fields, due in part to projection effects resulting from the height of the radio–emitting layer. Axes are labelled in arcseconds from apparent disk center.

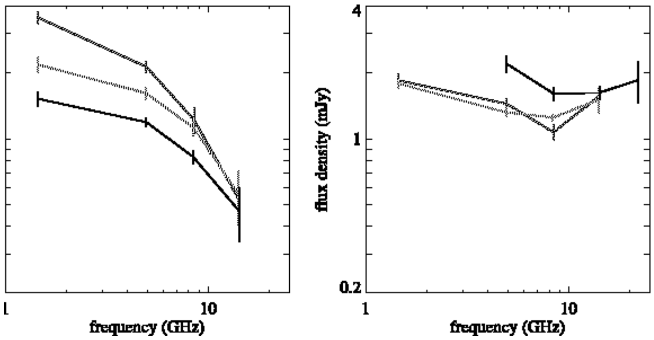

**Fig. 5.** Radio spectra of the active dMe star UV Cet during quiescence. The left figure shows three optically thin spectra falling with increasing frequency. These are typical of the nonthermal gyrosynchrotron emission from stars. The right figure shows rising spectra that are occasionally observed, indicating optically thick components above 10 GHz interpreted as gyroresonance emission (Güdel & Benz 1996).

## 4. Radio emission from starspots

Strong magnetic fields typically only occupy a few percent of the solar surface, and hence the filling factor of such fields in the solar corona is small. However, on active stars such as M dwarf flare stars, the filling factor of strong magnetic fields is much higher, possibly over 50%. This implies that the coronae of these stars may be optically thick over a very large area due to the same mechanism that operates in the solar corona. White, Lim & Kundu (1994) showed that photospheric magnetic field observations imply that the low corona of a dMe star should be saturated by magnetic fields with an average strength in excess of 1 kG. In such fields the hot component of the corona detected in X–ray observations (temperature of order $2 \times 10^7$ K) would be optically thick at least up to 15 GHz due to thermal gyroresonance opacity. The resulting emission would easily be detectable by radio observations, and should have a radio spectrum rising in the microwave range. An example of a spectrum consistent with this argument is shown in Figure 5 (Güdel & Benz 1989,1996).

However, most nearby M dwarfs detected as radio sources do not show such spectra: they are much more likely to show nonthermal gyrosynchrotron spectra like those shown in the left panel of Figure 5. Nonthermal synchrotron emission has different properties that mean it cannot easily yield magnetic field strengths. However, it does provide information on the magnetic field direction: the sense of circular polarization depends on whether the magnetic field in the radio source points towards or away from us. Observationally we find that each active star has its own characteristic sense of polarization that is observed repeatedly, i.e., the radio source always lies in a region with the same orientation of magnetic field. This would be a puzzling result if the magnetic field on the surface of the star was amde up of continually rapidly evolving, essentially bipolar active regions, in which case we would expect to see both senses of circular polarization from time to time. The observational data are much more consistent with the radio emission coming from a region dominated by a stable large-scale magnetic field, such as a global dipole field.

## 5. Present and future instrumentation

Coronal magnetic fields can best be observed at frequencies in the range 3 - 20 GHz, corresponding to field strengths 350 - 2400 G. At lower frequencies bremsstrahlung from dense coronal plasma can be optically thick and make it difficult to identify gyroresonance sources unambiguously. Coronal magnetic field strengths probably rarely exceed 2400 G, although the upper limit is completely unknown due to the lack of instrumentation; photospheric fields can reach 4000 G (e.g., Zirin & Wang 1993). At present there are at least five radiotelescopes used to study coronal magnetic fields above sunspots:

- **The Very Large Array (VLA)**: this telescope consists of 27 25m antennas operating at frequency bands at 0.075, 0.3, 1.4, 5, 8, 15, 22 and 43 GHz. It is the most sensitive and flexible and achieves the highest spatial resolution of the available telescopes. However, it is not solar-dedicated and is only used to observe the Sun a few percent of the time. In addition, the VLA is intended to cover a wide range of spatial scales by combining data from different configurations offered in 4-month blocks. While adequate for most resolved cosmic sources, which do not change on this timescale, this is not useful for the Sun and solar observations are forced to use data from just one configuration. The drawback is that a single configuration only covers a factor of about 20 in spatial scales; for the Sun, this means that one cannot simultaneously achieve high spatial resolution and high image quality, because at high spatial resolution one cannot reconstruct the emission from larger structures that dominate the flux.

– **The Nobeyama Radio Heliograph (NoRH)**: NoRH is designed to operate at high frequencies. It consists of 84 small antennas observing the complete solar disk at 17 GHz (dual circular polarization, resolution $15''$) and 34 GHz (single linear polarization at present, $8''$ resolution). It makes excellent images and routinely detects bright emission with coronal temperatures at 17 GHz from sunspots with coronal fields of 2000 G (Shibasaki et al. 1994). It has not detected sunspots at 34 GHz (which would require coronal fields of 4000 G).
– **The Owens Valley Solar Array (OVSA)**: This telescope is designed to observe the Sun with excellent frequency resolution. It uses a combination of large and small dishes to form images, and has demonstrated the potential value of observing at many closely-spaced frequencies simultaneously, but its image quality is limited by the small number of telescopes in the array.
– **The RATAN-600 radiotelescope**: This Russian radio telescope also observes at many frequencies (typically 40) in the range 1-18 GHz simultaneously, using a one-dimensional fan beam. It consists of 895 flat elements, each 2 by 11.5 m, arranged in a 600 m circle and illuminating movable secondary reflectors on railway tracks. Originally only capable of transit observations of the Sun (once daily at midday), it is being upgraded to be able to observe over a wider daily time range. It has demonstrated the presence of intriguing structure in the Sun's radio spectrum, particularly in the polarized component (e.g., Bogod et al. 2000).
– **The Siberian Solar Radio Telescope (SSRT)**: This relatively unknown telescope probably holds the record for the largest array presently operating, since it consists of 256 2.5m dishes. It operated as unconnected north-south and east-west one-dimensional arms until 1996, when it commenced two-dimensional observations (e.g., Uralov et al. 1998). Presently it operates at 5.7 GHz, but there are plans to expand the frequency range.

None of these telescopes is ideal for the study of the Sun. For this reason, work has started on a project to build such a radio telescope, FASR, described below. For the study of magnetic fields on more distant stars, really only the VLA has been useful, thanks to its sensitivity. However, most projects that can be carried out with the current VLA configuration have been attempted: study of stellar magnetic fields is limited to the nearest stars just due to the small radio fluxes involved. New breakthroughs will require a dramatic increase in sensitivity. Current microwave receivers are already operating at close to the theoretical quantum efficiency, so an increase in sensitivity can only be achieved in one of two ways: a large increase in the instantaneous bandwidth used in the observations (limiting flux $\propto$ bandwidth$^{-0.5}$); or a large increase in the collecting area of the telescope. Projects exploiting both these advances are being planned (EVLA using extra bandwidth, SKA with collecting area). We briefly describe these projects to end this review.

### 5.1. The Frequency Agile Solar Radiotelescope (FASR)

FASR (pronounced "phaser") is intended to be the next-generation solar radio telescope that combines the frequency agility of OVSA and RATAN 600 with the spatial resolution of the VLA and the full-disk coverage and sensitivity to a wide range of spatial scales embodied in NoRH. It will consist of $\sim$ 100 antennas in an array with maximum baselines of order 3 km providing spatial resolution of $1''$ at 20 GHz. The frequency range will be $\sim$ 0.2-30 GHz (the extremes of the range are still being decided on), and the study of coronal magnetic fields at high resolution is one of the main scientific objectives of FASR.

FASR will provide arcsecond-resolution full-disk images of the Sun at a large number of frequencies simultaneously. The data will be made publicly available in the form of processed images for both research, planning and synoptic purposes. High time resolution data (sub-second resolution) will be kept during periods of flaring. A wide range of data products will be made available to the solar and Space Weather communities in near real-time, including coronal magnetograms and coronal temperature maps derived using the ideas discussed above. Customized observing plans will also be possible.

FASR has been recommended as a high priority by the National Research Council Parker Committee on Ground-based Solar Research, and by the latest Astronomy and Astrophysics "Decade Report". Funding for startup activities has been awarded by the National Science Foundation, with Dale Gary (NJIT) as principal investigator. FASR should be operational by the next solar maximum, and will be a major supporting facility for space missions capable of studying the Sun's corona, such as STEREO and Solar-B. If no hard X-ray imaging space mission is launched for the next solar maximum, FASR will be the main instrument for imaging accelerated electrons in solar flares. The FASR web site may be found at `http://www.ovsa.njit.edu/fasr/`

### 5.2. The Expanded Very Large Array (EVLA)

With its flexibility, superior imaging ability and sensitivity, the VLA has been the workhorse of radio astronomy since it commenced operations 20 years ago. It has recently been recognized that the VLA must be enhanced if it is to maintain this role, and funding for such developments, known as the Expanded Very Large Array, has already started. There are two main steps to the expansion: the *Ultrasensitive Array*, which uses the existing VLA antennas with a major improvement in sensitivity and frequency coverage to be achieved by increasing the instantaneous bandwidth of the system and adding new receiver bands; and the *New Mexico Array*, which will involve the construction of 8 new antennas to be located across New Mexico and combined with existing antennas from the Very Long Baseline Array (VLBA) to improve the spatial resolution of the EVLA by a factor of 10. So far only the first stage of the expansion has been funded, consisting of the following steps:

- increase the bandwidth in each polarization from 0.1 to 8 GHz, using new fiber-optic signal transmission systems;
- build a new correlator both to handle the wider bandwidth and provide many more spectral channels than the present correlator;
- replace the current receivers with a new suite that covers the entire frequency range from 1 to 50 GHz, rather than the present receivers that are available only at selected narrow frequency bands in this range;
- and improve rejection of radio-frequency interference, necessary for operation at wide bandwidths.

The EVLA will be an order of magnitude more sensitive than the present VLA, allowing the study of coronal magnetic fields on a much wider range of stars and in much greater detail than is presently possible, and should be a great tool for stellar physics.

### 5.3. The Square Kilometer Array (SKA)

The developments at the Very Large Array will help studies of sources that produce continuum radio emission, such as stars, greatly because they benefit from the larger bandwidth. However, this does not improve sensitivity for spectral line sources, such as neutral hydrogen studies of rotation curves in galaxies, since the bandwidths of the spectral lines are fixed. For such sources, the only way to improve sensitivity is to build a telescope with a much larger collecting area, and radio astronomers around the world have been thinking about this development for a number of years now. This project has coalesced into an international effort known as the *Square Kilometer Array* (which has a number of web sites, e.g., `http://wwwatnf.atnf.csiro.au/projects/ska/`, `http://www.ras.ucalgary.ca/SKA/`). The VLA has a collecting area of 1.3 $\times$ $10^4$ m$^2$, and the Arecibo radio telescope in Puerto Rico (a large fixed dish located in a natural bowl in the ground) has an area of 7.3 $\times$ $10^4$ m$^2$. The goal of SKA is to build a telescope with a collecting area of $10^6$ m$^2$, operating in the frequency range 0.03 - 20 GHz.

A telescope this large will be enormously expensive, and it is recognized that no single country is likely to be able to construct it alone, so SKA is necessarily an international project. The engineering difficulties associated with such a project are also formidable, and a number of schemes have been suggested:

- arrays of many thousands of small inexpensive satellite-dish sized telescopes (e.g., 6 m) arranged in “fields” that will be combined electronically to synthesize a telescope consisting of a smaller number of elements but with the same collecting area. This scheme is being developed on a smaller scale for the Allen Telescope Array, a project of the SETI Institute that will be dedicated to the search for signals from extraterrestrial civilizations.
- an array of large Arecibo-like antennas located in a suitable region of China, which, like Arecibo, would only be able to track sources across a limited region of the sky;
- arrays of “Luneburg lenses”, large dielectric spheres that bring all frequencies to a focal point on the surface of the sphere. These elements are therefore intrinsically wideband. Tracking of sources would be achieved by moving a feed system across the face of the spheres on the opposite side from the source. This scheme has the disadvantage that the dielectric spheres themselves are very heavy, and achieving the necessary collecting area may be expensive.
- dirigibles carrying suites of receivers floating over large fields full of reflecting elements.

This project will also be a great instrument for the study of stellar magnetic fields due to its sensitivity and its ability to detect radio emission from magnetic fields on even more distant stars, but the timescale for this project is presently unknown.

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