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Searching for Extra-Solar Planets Using Non-Thermal Radio Continuum Emission

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Searching for planets by radiation detection opens up a whole new category of planets that can be discovered. With this method, planets as small as Jupiter and the earth have a greater chance of being revealed since their magnetospheres are large enough to make them very bright radio sources. The radiation power produced by the earth's auroral radiation is on the order of 10^7 W, and that of Jupiter's is on the order of 10^{10} W. With the completion of LOFAR, the detection of auroral radiation from Jovian-like planets in the 10MHz to 16MHz range will become possible.

I. INTRODUCTION

A. The history of extra-solar planet discovery

Within the last decade, more than 150 extra-solar planets have been discovered using a variety of techniques.

One of these techniques is the *Doppler Modulation* or *Radial Velocity Method*. As a planet moves around its star, the gravitational attraction between the two bodies causes the star to wobble around a fixed point. This wobble produces a shift in the star's stellar spectrum as seen by an observer. When the star moves towards the observer, the wavelength of the light is shortened and the star's spectrum is blueshifted. When the star moves away from the observer, the Doppler Effect creates redshift in the spectrum because of the resulting longer wavelength. Since the closest star is more than 1.5 parsecs away, only planets with a radius of 10^2 M_E to 10^3 M_E and within 0.1 - 1 AU of their host star have been detected using this method.

Another method that has been used is called *Occultation* or *Transit Photometry*. This method detects planets by looking for a periodic dimming in the star's brightness as the planet passes between the observer and the star. There is a greater probability of detecting planets with orbital periods of less than two years, because as a planet's distance from its star decreases, the possibility of the planet passing across the line of site from the observer to the star increases. [1]

B. Motivation for using the radio emission method

Like these two methods, many of the techniques currently used to identify planets are indirect in that they look for

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[1] Kepler Mission, http://www.keplermission.com/detection.html (2004)

the planet's effects on their host star. The reason for searching for extra-solar planets by detecting continuum radiation is in the hopes of establishing another method for direct observation. This method might also provide more detailed information about the planet such as its rotation period, whether it has satellites, its magnetic moment, and perhaps something about its atmosphere.

With the indirect methods, earth-like extra-solar planets have a very small chance of being detected because the planet has to be close enough to the star, and large enough such that its effects on the host star can be detected by us- the distant observers. Planets identified using these methods are usually not in the habitable zone of their host star, and have to large of a gravitational pull to sustain life.

With radio emission detection, planets as small as Jupiter and the earth, or even smaller, have a greater chance of being detected since their magnetospheres are large enough to make them very bright radio sources. In addition, because we do not fully understand how the magnetic fields of planets are created, there is no reason to discount the possibility that planets the size of the earth could have magnetic moments 10^2 times greater.

This method is not as restraining on the distance of the planet from its host star. Even though Jupiter is much farther from the sun, and therefore intercepts the solar wind when it is less dense than when the earth intercepts it, Jupiter is still a very strong radio source due to its gigantic magnetic field.

If planets of earth and Jupiter like sizes are detected using this method, many questions about the uniqueness of our solar system, and about our existence could be answered.

C. History of Extra-solar Giant (EGP) planet radio emission searches

There have been a few reported searches for radio emission from EGP's:

Dulk & Bastian used the *Very Large Array (VLA)* to observe six nearby stars at 333 and 1400 MHz (1986).

Bastian et al. reported on VLA observations of EGP and brown dwarf candidates at frequencies of 333 MHz, 1465 MHz, and 74 MHz. Some of the stars that were observed were 51 Peg, Ups And, 55 Cnc, 47 UMa, Tau Boo, 70 Vir and Lalande 21185 (2000).

Zarka & Ryabov reported their progress on observations of 20 nearby EGPs, using the UTR-2 array in the Ukraine (2003).[2]

However, no radio emission at these frequencies has been detected so far.

II. Magnetospheres and Radiation

A. Earth's Magnetic Field and Magnetosphere

The earth and many of the other planets in our solar system have a magnetic field. The source of a planet's magnetic field is still not completely understood, but it is thought to be explained by *dynamo theory*. In the case of the earth, this theory suggests that the field is produced by the convection and rotation of iron and nickel in the outer, liquid, metallic core. The electric current generated by this conducting fluid flowing across an existing magnetic field

[2] Stevens, Ian R. , Magnetospheric Rario Emission from Extra-solar Giant Planets: The Role of the Host Stars
Mon. Not. R. Astron. Soc., Oct. 25, 2004 (printed)

creates another magnetic field which reinforces the original one. This process is called a dynamo, and it creates a self sustaining magnetic field.

The outermost layer of the atmosphere is called the ionosphere. It extends from about 70 km above the ground to around 640 km.[3] It is composed of oxygen, hydrogen and nitrogen ions, and electrons which form a plasma. Recombination does occur, but the ionosphere's exposure to the sun's ultraviolet radiation reionizes any neutral atoms in a recurring cycle. More recombination occurs on the night side, but not very quickly because of the low pressure at these altitudes. The magnetic field of the earth interacts with this layer of the earth's atmosphere, because plasmas conduct electrical currents.

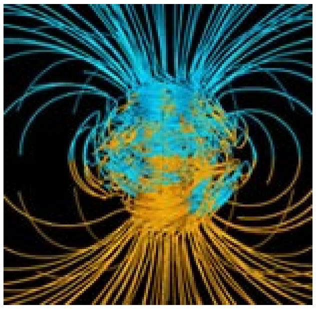

FIG. 1. 3D magnetic field structure simulated with the Glatzmaier-Roberts geodynamo model: lines are blue where field is directed inward and yellow where directed outward.
[SEDI's Image Library, http://www.agu.org/focus_group/SEDI/main/imagelib.html (2004)]

The sun also has a magnetic field which is produced by a similar mechanism. The sun looses mass at a semi-constant rate in the form of a continuous stream of plasma. This flow is called the solar wind, and it carries along with it some of the sun's weak magnetic field; maintaining the field lines at a roughly perpendicular angle to the its line of travel. The solar wind travels at around 600 km/s. This weak magnetic field, which fills the area surrounding the planets as the wind travels through the solar system, is called the *Interplanetary Magnetic Field (IMF)*. It is "frozen in" to the plasma because the plasma's electrical conductivity is very large which makes motion between it and the magnetic field impossible.

"For a simple analogy consider a conducting plate in a strong laboratory magnetic field. As soon as the plate is moved, electric currents are induced in it and these currents create another magnetic field which, by Lenz's law, interacts with the original field to oppose the original motion. In the hypothetical limit when the plate has infinite conductivity, the induced current is also infinite, the restoring force is infinite [F=Bil], and therefore no relative motion is possible.[4]"

To a first approximation, the earth's magnetic field would resemble that of a magnetic dipole if the planet was in vacuum. However, the solar wind and IMF come into contact with the earth's magnetic field. The magnetic field of the solar wind is unable to break through the geomagnetic field because it is already occupied by a highly conducting plasma. Therefore it is *frozen out* of the geomagnetic field. All it is able to do is alter its shape and size and creating what is called the solar-terrestrial environment. This distorted magnetic field is called the *magnetosphere*.

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[3] The Earth's Atmosphere, http://www.enchantedlearning.com/subjects/astronomy/planets/earth/Atmosphere.shtml (2005)

[4] Hargreaves, J. K. , The Solar-Terrestrial Environment (1992).

The boundary between the geomagnetic field and the approaching solar wind, called the magnetopause, can be determined using fluid mechanics. There is a pressure balance between the solar wind and the geomagnetic field. The energy density of the earth's magnetic field is given by

$$\rho_{em} = \frac{E}{V} = \frac{B^2}{2\mu_0} = \frac{\mu_0 M^2}{32\pi^2 r^6} \qquad (1)$$

where E is the geomagnetic field energy, V is volume, M is the earth's magnetic moment, r is the radius from the center of the planet, and B is the magnetic field of a dipole $B = (\mu_0 M)/(4\pi r^3)$ at a polar angle of $\theta = 90^o$.

The energy density of the solar wind is given by

$$\rho_{sw} = \frac{1}{2}\rho_m v^2 = \frac{\dot{M}_s v}{8\pi D^2} \qquad (2)$$

where ρ_m is the matter density of the solar wind [$\rho_m = (\dot{M}_s)/(4\pi D^2 v)$], M_s is the mass loss of the sun, v is the velocity of the solar wind, and D is the distance between earth and the sun. The mass loss of the sun $\dot{M}_s$ = 10^9 kg/s, the distance from the earth to the sun D = 1.5x10^11m, and the magnetic moment of the earth M = 6.7x10^22m²A. Setting ρ_{em} equal to ρ_{sw} and solving for r gives

$$r = \left(\frac{\mu_o}{4\pi} \frac{M^2 D^2}{\dot{M}_s v} \right)^{\frac{1}{6}} \qquad (3)$$

When this equation is solved, r = 6x10^7m = 10R_E (the radius of the earth, R_E =6x10^6m). This means that the magnetosphere extends 10 earth radii out on the side of the earth that faces the incoming solar wind.

The magnetosphere is a sold object in comparison to the solar wind. Therefore, like the air surrounding an aircraft traveling at supersonic speeds, the solar wind creates a shock about 2-3R_E in front of the magnetopause called the bow shock. The solar wind is slowed down to around 250 km/s after crossing the bow shock. This decrease in velocity results in an increase in kinetic energy and density. The solar wind is redirected to flow around the magnetopause; and this region, between the bow shock and magnetopause, is called the magnetosheath.

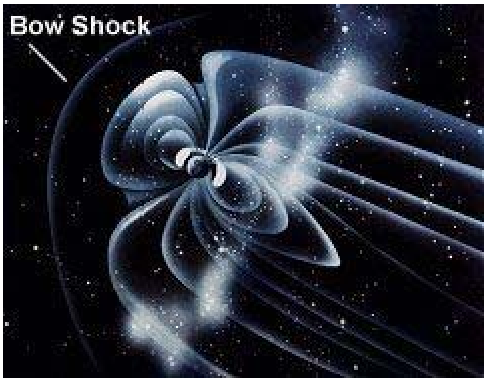

FIG. 2. An image of what the bow shock might look like if we could see it. (Image not drawn to scale) [Seeing the Invisible, http://science.nasa.gov/newhome/headlines/ast27oct98_1.htm (1998)]

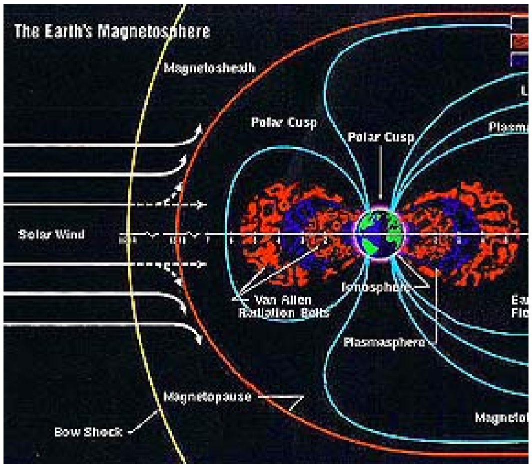

FIG. 3. This image shows the solar wind being deflected around the magnetopause and forming the magnetosheath region. [Nasa website, http://see.msfc.nasa.gov/pf/pf.htm (2005)]

The solar wind distorts the magnetic field of the earth because it attempts to drag it along as it does with the sun's magnetic field. However, since the magnetic field of the earth is very strong, the solar wind is only able to reshape it. The magnetic field strength on the day side is doubled because of the compression due to the solar wind pressure. The magnetic field on the night side is stretched out, and it extends beyond 10^3 earth radii. This region is called the magnetotail.

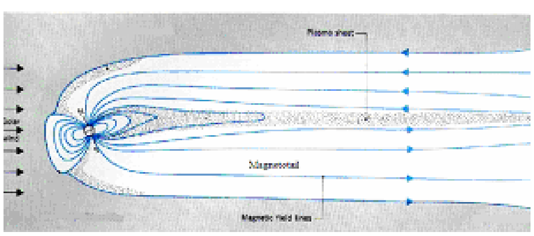

FIG. 4. A picture of the earth's magnetotail [Planet Earth, http://www.stcloudstate.edu/~physcrse/astr106/earthxpcy2.html (1997)]

A simple mathematical model that can be used to approximate the reshaped geomagnetic field is called the *image dipole*. In this model, the solar wind and its magnetic field are represented by an "image dipole" of magnetic moment $M_I = 28M$ placed at a parallel distance of $40R_E$ from the earth's dipole. The fields are added, and the altered field lines of the earth's dipole represent the magnetosphere. This model does not represent the field of the magnetotail. See APPENDIX A: IMAGE DIPOLE MODEL EQUATIONS for the equations of the magnetosphere using the image dipole method in cartesian and spherical form.

Some of the magnetic field lines that would connect in front on the day side of the earth are swept back and form the outer boundaries of the magnetotail.

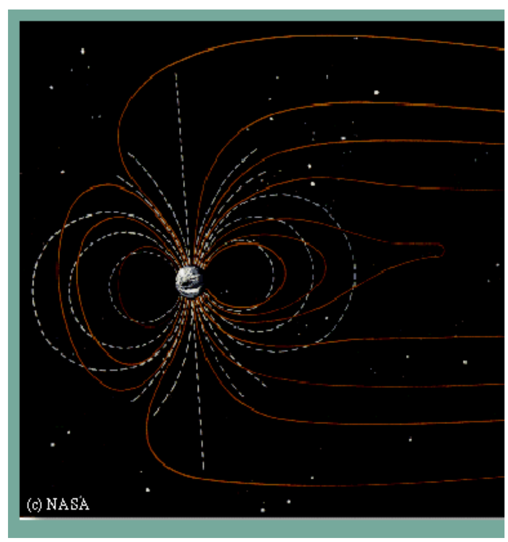

FIG. 5. This shows the reshaping of the earth's magnetic field from a dipole to the magnetosphere due to its interaction with the solar winds. [Learning about the Aurora, http://sprg.ssl.berkeley.edu/~cyclopi/lesson1.html (2002)]

1. Earth's auroral radiation

The field lines in between these two regions connect the earth's surface at 78° geometric latitude to the magnetopause, and form neutral points where the total field is zero.

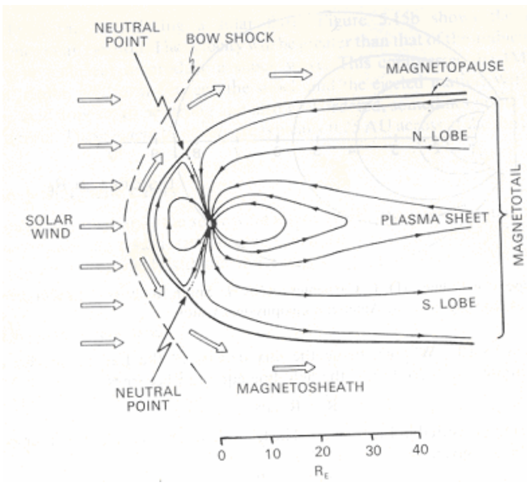

FIG. 6. An illustration of the neutral points. [Hargreaves]

Here reconnection can occur between these magnetic field lines and those of the IMF. Reconnection mostly occurs when the IMF is pointing southward, but some reconnection can occur when it is pointing northward. This reconnection takes place in the north and south pole, and the regions it forms are called polar cusps. These are the only places where solar wind plasma particles can enter the magnetosphere. Electrons are accelerated down into the cusps by strong electric fields aligned parallel to the magnetic field.

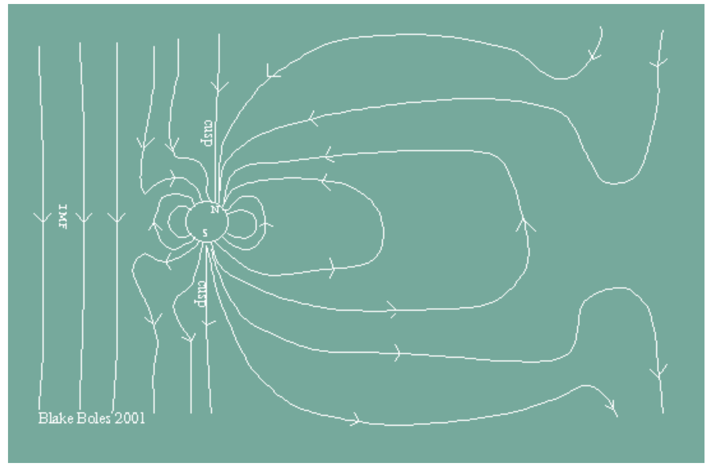

FIG. 7. This figure illustrates the reconnection that takes place between a south pointing IMF and the polar region's magnetic field lines. [Learning about the Aurora]

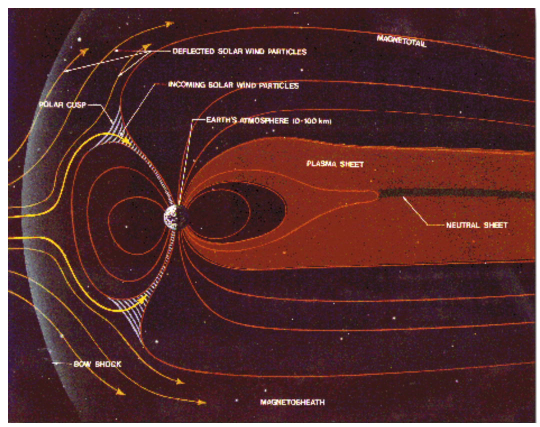

FIG. 8. This picture shows the cusp region. [The Weatherman in Space http://science.nasa.gov/NEWHOME/HEADLINES/ast29oct98_1.htm (1998)]

One theory for the production of this electric field involves the pitch angles of the incoming particles. The pitch angle is the ratio of a particle's perpendicular velocity to its parallel velocity in relation to the magnetic field. A greater pitch angle means a greater rotational velocity.

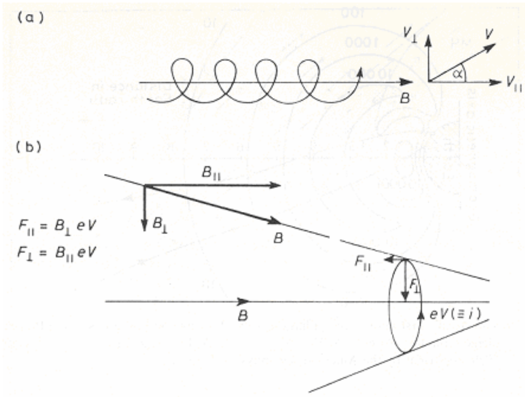

FIG. 9. (a) the pitch angle (b) the force due to a converging magnetic field. [Hargreaves]

As a charged particle spirals down a magnetic field line, the pitch angle increases until it reaches a point where its velocity is completely perpendicular to the magnetic field. At this point, the mirror point, forward motion stops. The particle is reflected back along the field line because of the converging magnetic field which produces a force perpendicular to the looping particle. The mirror point of a charged particle is determined by the pitch angle.

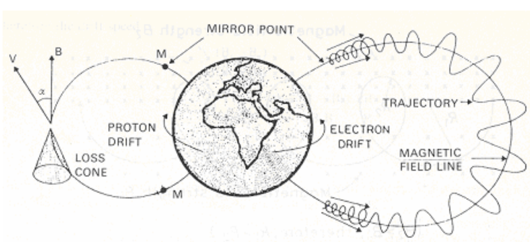

FIG. 10. When a charged particle bounces back and forth along a field line between its mirror points, it is said to be trapped by the magnetic field. [Hargreaves]

The pitch angle of the ions in the solar wind is greater than that of the electrons. Since the ions have a greater pitch angle, they will mirror lower than the electrons. This creates a charge separation and upward pointing electric field which accelerates other electrons past their mirror points and drives them into the ionosphere. These electrons are responsible for the auroral displays. The electric field is maintained because of the continuous influx of magnetosheath particles. [5]

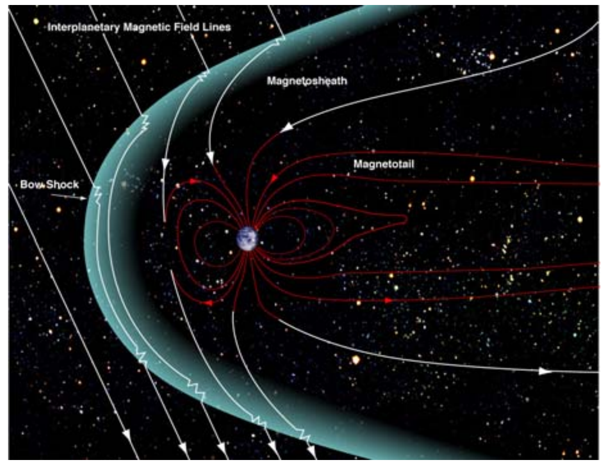

FIG. 11. An illustration of the IMF- geomagnetic field reconnection. [The Magnetosphere, http://ssdoo.gsfc.nasa.gov/education/lectures/magnetosphere.html (2005)]

As these electrons spiral down through the magnetic field, they produce kilometric cyclotron radiation. This radiation is called *Auroral Kilometric Radiation (AKR)*. In the region where this radiation is produced (1.025 R_E to 3 R_E) the field can be approximated as a pure dipole. The field at 2R_E is 9.6x10^(-6)T. (See APENDIX B: MAGNETIC FIELD STRENGTH IN CUSP AT 2R_E for this calculation.) The, angular frequency, frequency and wavelength of the radiation are

$$\omega = \frac{eB}{m} = 1.7\text{x } 10^{6}\, s^{-1} \qquad (4)$$

[5] Boles, Blake; Learning About the Aurora http://sprg.ssl.berkeley.edu/~cyclopi/lesson1.html (2002).

$$f = \frac{\omega}{2\pi} = 300\text{kHz} \quad (5)$$

$$\lambda = \frac{c}{f} = 1\text{km} \quad (6)$$

where e is the charge of the electron, m is its mass, f is the frequency of the radiation, c is the speed of light, and λ is the wavelength of the radiation. The radiation is termed kilometric because of its wavelengths of around 1 to 2 kilometers. This elliptically polarized radiation travels up through the magnetosphere and into space where it can be detected.

B. Magnetic field and magnetosphere of the other planets

It is possible for a planet to have a magnetosphere even if it does not have a magnetic field. In this case, its magnetosphere is formed by the interaction of the solar wind with its upper atmosphere. Mars and Venus do not have magnetic fields, but their upper atmospheres interact with the solar wind.

Mercury, Jupiter, and Saturn, Neptune, and Uranus have magnetic fields. The differences between their magnetospheres and Earth's are due to different magnetic moments and distances from the sun (which produce different solar wind pressures).

Jupiter and Saturn have larger magnetic moments than the Earth. In addition, they are a greater distance from the sun which means that their magnetopauses extend farther out in the sunward direction. Therefore the planet's rotation has a greater effect on the shape of its magnetic field, and a more dipole like shape is maintained.

On the other hand, Mercury is very close to the sun, and has a very weak magnetic field. Therefore its magnetopause is very close to its surface. Due to this and the fact that it has no atmosphere, particles circulating in its magnetosphere can hit the planet directly.

Hence, the earth provides an intermediate case where its inner magnetic field is controlled by its rotation and its outer field is controlled by its interaction with the solar wind.

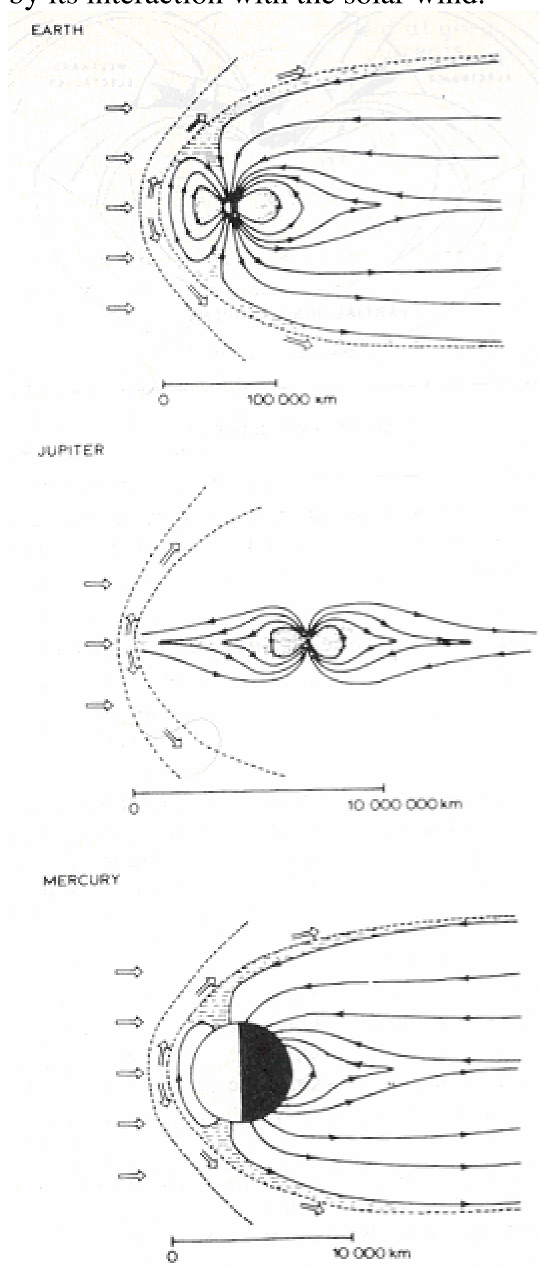

FIG. 12. A comparison between the magnetospheres of the Earth, Jupiter and Mercury. [Hargreaves]

1. Jupiter's auroral radiation

Jupiter produces a type of radiation from its polar region that is the equivalent of the Earth's AKR. It is called the *Jovian Hectometric Radiation (JHR)*. Just like on earth, this continuous, elliptically polarized, cyclotron emission is generated along auroral magnetic field lines at altitudes of $1R_J$ to $3\ R_J$, and is controlled by the solar winds. Periods of enhanced JHR are preceded by periods of enhanced solar wind density.

The frequency range of emission is 0.5MHz to 16MHz. The range of the most intense hectometric radiation is 0.5MHz to 5.6MHz. The emission locations do not drift in longitude but rotate with the Jovian magnetosphere.[6]

C. Procedure for determining the earth's auroral kilometric radiation power

Since the electrons have a smaller pitch angle than the ions, more of their velocity is directed along the electric field, so we can use the approximation that the electric field accelerates the electron from its initial velocity.

The parallel electric field accelerates the electrons from 100eV to 1keV as they spiral down into the cusp. 100eV is equal to 1.6x10^-17J and corresponds to a velocity of .45x10^7m/s. 1keV is equal to 1.6x10^-16J and corresponds to a velocity of 1.9x10^7m/s. Therefore the electrons' average velocity is 1.2x10^7m/s.

The centripetal acceleration, a, of the electron as it spirals in the magnetic field is determined from the equations below

$$r_B = \frac{m_e \bar{v}}{Be} \qquad (7)$$

$$a = \frac{\bar{v}^2}{r_B} = \frac{Bev}{m_e} = 2x10^{13} m/s^2 \qquad (8)$$

where $\bar{v}$ is the average velocity, m_e is the mass of an electron, B is the magnetic field at $2R_E$ (see APPENDIX B), and r_B is the radius of the circular motion.

The Lorentz equation determines the power radiated by an electron spiraling in a magnetic field

$$P = \frac{\mu_o q^2 a^2}{6\pi c} = 2.28x10^{-27}\ W/electron \qquad (9)$$

The volume of the cusps where the electrons radiate is found as follows: The magnetopause cusp area, located at $10R_E$, is $\pi(.5R_E)^2 = 2.8x10^{\wedge}13m^2$. The area of the cusp at auroral heights ($1R_E$) is related to the area at the pause by

$$A_l = \left(\frac{B_u}{B_l}\right) A_u = \left(\frac{5x10^{-8}T}{5x10^{-5}T}\right)\left(2.8x10^{13}m^2\right) = 2.8x10^{10}m^2 \qquad (10)$$

where A_l and B_l are the area and magnetic field strength at $1R_E$, and A_u and B_u are those at $10R_E$. From A_l, the radius at this height is found to be 9.5x10^4m. The shape of the cusp region can be approximated by a cone, and the radius of the cross sectional area

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[6] Control of Jupiter's Radio Emission and Aurorae by the Solar Wind, http://www.nature.com/cgi-taf/DynaPage.taf?file=/nature/journal/v415/n6875/full/415985a_fs.html (2002).

of the cone at $3R_E$ can be found through the relationship of similar triangles.

$$\left(\frac{r_l}{h_l}\right)=\left(\frac{r_m}{h_m}\right)\rightarrow\left(\frac{9.5x10^4 m}{1R_E}\right)=\left(\frac{r_m}{3R_E}\right)$$

$$r_m = 2.85x10^5 m \qquad (11)$$

With these values, the volume of the cone where the electrons radiate can be found.

$$V_r = V_c - V_{sub} = \frac{\pi}{3} r_m^2 h_m - \frac{\pi}{3} r_l^2 h_l = 1.4x10^{18} m^3 \qquad (12)$$

Some of the electrons have such a small pitch angle that they mirror before the electric field can accelerate them past their mirror points. These electrons bounce back and forth between their mirror points in the north and south poles.

The electron density in the radiating volume is very high because of these trapped electrons, and the continuous influx of solar winds. The electron density is 2.3x10^16m^(-3). From this value, the total number of electrons in the radiating volume is calculated to be 3.2x10^34, and the radiation power produced by these electrons is

$$P_{rad} = 2.28x10^{-27}\,W/electron\ x\ 3.2x10^{34} electrons = 7.3x10^7\,W \qquad (13)$$

This value agrees with the *Radiometric Bode's Law* which states that

$$P_{rad} = \varepsilon P_{isw} \qquad (14)$$

where P_{isw} is the solar wind power incident on the magnetosphere, and ε is a constant whose value is 10^(-5). This value was determined experimentally from data on the Earth's and the Gas Giants' auroral radiation. For the Earth

$$P_{isw} = \rho_{sw}\ x\ (SA)_{inc}\ x\ v = \rho_{sw}\ x\ \pi r_{mag}^2\ x\ v = \frac{M_s}{8}\left(\frac{R_{mag} v}{D}\right)^2 = 7.2x10^{12}\,W \qquad (15)$$

$$P_{rad} = \varepsilon P_{isw} = 10^{-5} x\left(7.2x10^{12}\,W\right) = 7.2x10^7\,W$$
(16)

where R_{mag} is the radius of the magnetosphere.

D. Jupiter's hectometric radiation power

Since

$$P_{rad} = \varepsilon \frac{M_s}{8}\left(\frac{R_{mag} v}{D}\right)^2 \qquad (17)$$

and all of these values are known for Jupiter, the power of the JHR can be determined. $R_{mag} = 70R_j = 4.9x10^9 m$, and D = 7.8 x10^11m. Therefore, P_{rad} = 1.8x10^10W.

III. Candidate Stars for the Radio Emission Method

Recently, a study has been done to determine the stars within 10 parsecs of our solar system that have the greatest possibility of sustaining life on a planet of the proper size within its *Continuously Habitable Zone (CHZ)*. The stars were judged by their atmospheric parameters, chemical composition, degree of chromospheric activity, state of their evolution, mass, age, orbit eccentricity, ect.

The thirteen stars that they felt future space based missions should consider for searching for Earth-like extra-solar planets were named "biostars." They represents 7% of all the stars within 10 parsecs of our solar system. Three of these stars: ζ Tucanae (HD 1581), β Comae Berenicis (HD 109358), and 61 Virginis (HD 115617), were the best candidates because their properties were the closest to our Sun's in terms of evolutionary status, chemical composition, age, and mass. The other 10 stars in the order of their ranking are δ Pav (HD 190248), HD 192310, HD 219134, HD 16160, HD 4628, 107 Psc (HD 10476), HD 32147, HD 102365, HD 100623, σ Draconis (HD 185144).[7]

III. Radio Telescopes

The possible wavelengths of operation for ground based telescopes are 1mm (f = 300GHz) to 10m (f = 30 MHz). A process called scintillation occurs for wavelengths of 20 cm and higher where irregularities in the ionosphere distort the incoming signal, however, some telescopes can adjust for varying degrees of these irregularities. At wavelengths less than 3cm, absorption in the atmosphere becomes increasingly critical. At wavelengths less than 1cm, ground based observations are only possible at certain wavelength bands that do not have atmospheric absorption. For wavelengths greater than 10m, the ionosphere makes ground based observations impossible. For wavelengths from 1cm to 20cm, ground based observations are the least distorted.[8]

A. Current Radio Telescopes

1. The Very Large Array (VLA)

The VLA is located in New Mexico, and is part of the *National Radio Astronomy Observatory (NRAO)*. It consists of 27 radio antennae which have a 25m dish diameter and weigh 230 tons. The antennae are arranged in the shape of a Y. Each of the arms of the Y are 21km long. The array has four configurations (A-D) and can be arranged to have a maximum baseline of 36 km; therefore the array can act like a single antennae with this diameter. Its greatest angular resolution is 0.05 arcseconds.[9] The VLA's frequency coverage is from 74MHz to 50,000MHz. Its sensitivity is $\frac{1}{10}$ mJy = $1x10^{-4}\,\mathrm{Jy} = 10^{-30}\,\mathrm{Wm^{-2}Hz^{-1}}$.

The flux per unit frequency emitted by a Jupiter-like planet at 10 parsecs from its observer is determined as follows:

$$F_f = \frac{L_f}{4\pi D_{JO}^2} \tag{18}$$

$$L_f = \frac{\varepsilon \dot{E}}{f} \tag{19}$$

$$\dot{E} = \frac{1}{2}\dot{M}_s v^2 \frac{\pi R_{mag}^2}{4\pi D_{SJ}^2} = \frac{1}{8}\dot{M}_s \left(v \frac{R_{mag}}{D_{SJ}} \right)^2 \tag{20}$$

$$F_f = \frac{\varepsilon \dot{M}_s}{32\pi f}\left(\frac{v R_{mag}}{D_{JO} D_{SJ}}\right)^2 = 3x10^{-32}\,\mathrm{Wm^{-2}Hz^{-1}}$$
(21)

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[7] G. Porto de Mello, E. Fernandes del Peloso, and L. Ghezzi, Astrobiologically Interesting Stars within 10 parsecs of the sun (2005).
[8] NRAO, How Radio Telescopes Work, http://www.nrao.edu/whatisra/radiotel.shtml (2005).

[9] Wikipedia The Free Encyclopedia, http://en.wikipedia.org/wiki/Very_Large_Array (2005).

where L_f is the luminosity per unit frequency, $\dot{E}$ is the energy received by the telescope, f is the frequency, D_{JO} is the distance between Jupiter and an observer, and D_{SJ} is the distance between the sun and Jupiter.

The flux per unit frequency received by the observer is slightly less than what the VLA can detect. Therefore, if the VLA could detect auroral hectometric radiation, it would be able to detect radiation from a Jovian-like planet that has a bigger magnetic field. A larger magnetic field translates into a larger R_{mag} and therefore a larger F_f .

B. Future Radio Telescopes

1. Ground Based Telescopes

(a) Low Frequency Array (LOFAR)
LOFAR is a project that is currently being built across the Netherlands and North Germany. This large radio telescope array will operate between wavelengths of 1.25m (f = 240 MHz) and 30m (f = 10MHz). Its 25,000 dipole antennas will cover a region 350 km across. It will have a total collecting area of $1km^2$ at 15MHz with a one arcsecond angular resolution. [10]

LOFAR will be completed soon and will have a greater sensitivity than the VLA. Therefore, it could be used to detect auroral radiation from Jovian-like planets around other stars in the 10MHz to 16MHz range.

IV. Conclusion

In conclusion, auroral radio emission detection is a promising method for discovering planets. Anticipating the completion of future radio telescopes like LOFAR, a search for Jovian-like extra-solar planets could be carried out in the near future.

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APPENDIX A: IMAGE DIPOLE MODEL EQUATIONS[11]

$r'^2=(x-2a)^2 + y^2 + z^2$
$B_o = -30{,}574nT*R_E^3$
conic section of $\varepsilon=\infty$

A. Cartesian

$$B_x= 3B_o\left[\frac{xz}{r^5}+\frac{(x\text{-}2a)z}{r'^5}\right] \quad \text{(A1)}$$

$$B_y= 3B_o\left[\frac{yz}{r^5}+\frac{yz}{r'^5}\right] \quad \text{(A2)}$$

$$B_z= B_o\left[\frac{(3z^2-r^2)}{r^5}+\frac{(3z^2-r'^2)}{r'^5}\right] \quad \text{(A3)}$$

B. Spherical

a=distance from center of Earth to leading edge of particle front

[10] LOFAR Homepage General Information, http://www.lofar.org/p/geninfo.htm (2005).

[11] Petrinec, S. M., Ph.D. thesis, University of California at Los Angeles, 1993, p. 406-7.

φ=0° along Sun-Earth line increasing towards dusk side of planet
θ = polar angle measured from north pole

$$B_r = 2B_o\cos(\theta)\left[\frac{1}{r^3} + \frac{1}{r'^3} + \frac{(3ar\sin(\theta)\cos(\varphi) - 6a^2)}{r'^5}\right]$$
(A4)

$$B_\theta = B_o\sin(\theta)\left[\frac{1}{r^3} + \frac{1}{r'^3} - \frac{6ar\cos(\theta)\cot(\theta)\cos(\varphi)}{r'^5}\right]$$
(A5)

$$B_\varphi = \frac{6B_o ar\cos(\theta)\sin(\varphi)}{r'^5} \qquad \text{(A6)}$$

APENDIX B: MAGNETIC FIELD STRENGTH IN CUSP AT 2R$_E$

θ=12°=.21
r=2R$_E$
R$_E$=6x10^6m

$$B_r = \frac{2B_o\cos(\theta)}{r^3} = 7.5\text{x}10^{-6}\text{T} \qquad \text{(B1)}$$

$$B_\theta = \frac{B_o\sin(\theta)}{r^3} = 6\text{x}10^{-6}\text{T} \qquad \text{(B2)}$$

$$B_\varphi = 0\text{T} \qquad \text{(B3)}$$

$$B = \sqrt{B_\theta^2 + B_r^2} = 9.6\text{x}10^{-6}\text{T} \qquad \text{(B4)}$$

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