Flat-spectrum Radio Continuum Emission Associated with \( \epsilon \) Eridani

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Abstract

We present Very Large Array observations at 33.0 GHz that detect emission coincident with \( \epsilon \) Eridani to within 0.007 (0.2 au at the distance of this star), with a positional accuracy of 0.005. This result strongly supports the suggestion of previous authors that the quiescent centimeter emission comes from the star and not from a proposed giant exoplanet with a semimajor axis of \( \sim 1.7 \) (3.4 au). The centimeter emission is remarkably flat and is consistent with optically thin free–free emission. In particular, it can be modeled as a stellar wind with a mass-loss rate of the order of \( 6.6 \times 10^{-11} M_\odot \text{yr}^{-1} \), which is 3300 times the solar value, exceeding other estimates of this star’s wind. However, interpretation of the emission in terms of other thermal mechanisms like coronal free–free and gyroresonance emission cannot be discarded.

Key words: radio continuum: stars – stars: individual (\( \epsilon \) Eri)

1. Introduction

At a distance of only 3.2 pc (van Leeuwen 2007), \( \epsilon \) Eridani is one of the stars nearest to the Sun. It has a spectral type of K2V (Keenan & McNeil 1989) and an age that has been estimated to be between 0.4 and 1.4 Gyr (Soderblom & Dappen 1989; Soderblom et al. 1991; Janson et al. 2008; Mamajek & Hillenbrand 2008; Bonfanti et al. 2015). The detection of a debris disk (Greaves et al. 1998; Holland et al. 1998; Chavez-Dagostino et al. 2016) located at \( \sim 64 \) au from the star with a width of \( \sim 20 \) au has stimulated many papers that study \( \epsilon \) Eridani.

More recently, it has been found that there is continuum emission at millimeter and centimeter wavelengths associated with the star (MacGregor et al. 2015; Chavez-Dagostino et al. 2016; Bastian et al. 2018). It has been suggested that the emission close to the star can instead be attributed to one (or two) inner warm dust belts (Backman et al. 2009; Reidemeister et al. 2011), although the results of Chavez-Dagostino et al. (2016) indicate that the contribution of such a component might be marginal.

The centimeter continuum emission was detected and discussed in detail by Bastian et al. (2018). From radial velocity analyses of \( \epsilon \) Eridani, the presence of one giant exoplanet with semimajor axis of 3.4 au (\( \sim 1'' \)) has been proposed (Hatzes et al. 2000; see also Mawet et al. 2018). The reality of this exoplanet, however, remains controversial (Anglada-Escude & Butler 2012). In any case, Bastian et al. (2018) analyzed the quiescent and flaring radio continuum emission considering that the K2V star or the Jupiter-like planet were the sources. While they could not rule out a planetary origin based on the radio source position, the nature of \( \epsilon \) Eridani as a moderately active “young Sun” favors a stellar origin.

A direct way to distinguish between a stellar and a planetary origin is to obtain high-angular-resolution observations of the radio emission and compare the radio position with the stellar position. A significant displacement between the two would favor a planetary origin, while a close coincidence will favor a stellar origin. The previous radio observations of the emission associated with \( \epsilon \) Eridani did not have sufficient angular resolution to discriminate between the two possibilities. Here we present such observations. We also discuss the nature of the radio emission. The broad bandwidth and high sensitivity of the available observations enable a detailed characterization of the spectral energy distribution, unprecedented for a young, low-mass star.

2. Observations

The observations were made with the Karl G. Jansky Very Large Array (VLA) of NRAO\(^6\) centered at a rest frequency of 33.0 GHz (9.1 mm) during 2017 June 15. At that time the array was in its C configuration, providing an angular resolution of \( \sim 1'' \). The phase center was at \( \alpha(2000) = 03^{h}32^{m}54^{s}84; \delta(2000) = -09^\circ 27' 29'' 7 \). The flux and bandpass calibrator was J0542+4951, and the phase calibrator was J0339−0149. The total observing time was 60 minutes, of which 28 were on-source.

The digital correlator of the VLA was configured in 64 spectral windows of 128 MHz width divided into 64 channels with a spectral resolution of 2 MHz. The total bandwidth for the continuum observations was about 8.0 GHz in a dual-polarization mode.

The data were analyzed in the standard manner using the Common Astronomy Software Application package of NRAO using the pipeline provided for VLA\(^7\) observations. Maps were made using a robust weighting (Briggs 1995) of zero in order to...
optimize the compromise between sensitivity and angular resolution. The resulting image rms was 9.0 μJy beam⁻¹ at an angular resolution of 0°85 × 0°51 with PA = −31°1. In Figure 1 we show the 33.0 GHz emission associated with ε Eridani. The radio source appears unresolved with a flux density of 70 ± 9 μJy. The error given here includes only the statistical error. A more realistic total error estimate would include a 10% systematic error added in quadrature, giving a flux density of 70 ± 11 μJy.

Table 1 summarizes the centimeter and millimeter observations of ε Eridani that will be discussed below. The first column is the instrument, the second column is the epoch of observation, the third column is the frequency band, the fourth column is the flux density, the fifth column is an upper limit to the circular polarization, and the sixth column is the reference.

2.1. Field Sources at 10 GHz

Chavez-Dagostino et al. (2016) detected a total of seven sources at 1.1 mm in a field of ~3' × 2.5 centered on ε Eridani. To search for centimeter counterparts to these sources, we also reduced and analyzed the 3 cm (10 GHz) Jansky VLA data taken as part of project 13A-471. These observations were taken on 2013 April 20, May 18, and May 19 with the VLA in the D configuration. The data were calibrated and concatenated to produce a deep image with noise of ~3 μJy at the center of the field. We detected a total of 16 sources whose positions, flux densities, and counterparts are given in Table 2. Only three of these sources have previously known counterparts. VLA source 2 coincides positionally with the galaxy 6dFGS gJ033243.6-093557 (Jones et al. 2009). VLA source 6 coincides with ε Eridani. Finally, VLA source 11 coincides within ~2'' with millimeter source 5 in the list of Chavez-Dagostino et al. (2016).

3. Comparison of Radio and Optical Positions

We fitted the radio image with a Gaussian ellipsoid, obtaining a position of α(2000) = 03°32′54.7067 ± 00′′.0022; δ(2000) = −09°27′29.288 ± 0′′.032. The uncertainties in this position are the statistical noise resulting from the least-squares fit. To compare with this position, we used the Hipparcos position (van Leeuwen 2007) and corrected it for proper motions and parallax to the epoch of the radio observations. Taking into account the propagation of the astrometric errors, the Hipparcos data imply α(2000) = 03°32′54.7046 ± 00′′.0003; δ(2000) = −09°27′29′′.288 ± 0′′.0004 at the epoch of the VLA observations. This position is shown with a cross symbol in Figure 1 overlaid on the radio emission. The difference between the Hipparcos and VLA positions is given by

\[ \Delta\alpha(\text{Hipparcos} - \text{VLA}) = -0.0021 ± 0.0022, \]

\[ \Delta\delta(\text{Hipparcos} - \text{VLA}) = 0.0060 ± 0.0032. \]

Since the separation between the Hipparcos and VLA positions is within 1σ to 2σ of the positional error, we conclude that the positions can be considered to be coincident at the level of 0.07 (0.2 au at the distance of ε Eridani) and that this comparison rules out the possibility that the radio emission is coming from a position displaced more than 0.2 au from the star. The proposed giant exoplanet would have a semimajor axis of 3.4 au (Hatzes et al. 2000) and thus would appear most of the time to be displaced more than 0.2 au from the star. We, therefore, support the suggestion of Bastian et al. (2018) that the emission has a stellar origin. Note that, while we reach this conclusion on the basis of position coincidence, Bastian et al. (2018) reached the same conclusion from the fact that the observed radio emission is consistent with known mechanisms of stellar emission.

4. The Nature of the Radio Emission

In Figure 2 we show the spectrum of the emission associated with ε Eridani in the centimeter and millimeter ranges. These flux densities are taken from Bastian et al. (2018), MacGregor et al. (2015), Lestrade &Thilliez (2015), Booth et al. (2017), Chavez-Dagostino et al. (2016), and this paper (see Table 2). In the case of the observed millimeter emission, the rapid rise of the flux density with frequency (a spectral index of 4.9 ± 1.8) favors emission from warm dust (e.g., Ricci et al. 2010). In contrast, the centimeter emission is remarkably flat (a spectral index of ~0.07 ± 0.25), suggesting an optically thin free–free nature. Below we examine the expected properties of the free–free emission.

4.1. Optically Thin Free–Free Emission

The free–free power per unit volume per Hz is given by

\[ \epsilon_\nu^{ff} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} \exp(-\hbar \nu / k T) \bar{g}_{ff} \times \text{erg s}^{-1} \text{cm}^{-3} \text{Hz}^{-1}, \]

(1)

where \( Z \) is the ion charge, \( n_e \) and \( n_i \) are the electron and ion number density, respectively, \( T \) is the plasma temperature, and \( \bar{g}_{ff} \) is the velocity-averaged Gaunt factor.
Table 1
Flux Densities of ε Eridani

| Instrument | Epoch             | Band (GHz) | Flux density (µJy) | ρ₂b | References     |
|------------|-------------------|------------|--------------------|-----|----------------|
| VLA        | 2016 Mar 1        | 2–4        | <65b               | ... | Bastian et al. (2018) |
| VLA        | 2016 Jan 21       | 4–8        | 83 ± 16.6          | <50 | Bastian et al. (2018) |
| VLA        | 2013 May 18       | 8–12       | 66.8 ± 3.7         | <14 | Bastian et al. (2018) |
| VLA        | 2013 May 19       | 8–12       | 70.3 ± 2.7         | <10 | Bastian et al. (2018) |
| VLA        | 2013 Apr 20       | 12–18      | 81.2 ± 6.6         | <20 | Bastian et al. (2018) |
| VLA        | 2017 Jun 15       | 29–37      | 70 ± 11            | <22 | This paper       |
| ATCA       | 2014 Jun 25 to Aug 5 | 42–46  | 66.1 ± 8.7         | ... | MacGregor et al. (2015) |
| SMA        | 2014 Jul 28 to Nov 19 | 217–233 | 1060 ± 300        | ... | MacGregor et al. (2015) |
| IRAM       | 2007 Nov 16 to Dec 4 | 210–290 | 1200 ± 300        | ... | Lestrade & Thilliez (2015) |
| ALMA       | 2015 Jan 17 to Jan 18 | 226–234 | 820 ± 68          | ... | Booth et al. (2017) |
| LMT        | 2014 Nov 1 to Dec 31 | 245–295 | 2300 ± 300        | ... | Chavez-Dagostino et al. (2016) |

Notes.

a 2.5σ upper limit for percentage of circular polarization.
b 2.5σ upper limit for quasi-steady emission.

Table 2
Sources Detected at 10 GHz

| Position   | α2000 (h m s) | δ2000 (° ′ ″) | Flux densityb (µJy) | Counterpart |
|------------|---------------|---------------|---------------------|-------------|
| 1a         | 03 32 30.97   | −09 24 30.9   | 3600 ± 500         | ...         |
| 2a         | 03 32 43.53   | −09 35 56.7   | 240 ± 40           | 6dFGS       |
| 2b         | 03 32 43.53   | −09 35 56.7   | 240 ± 40           | gJ033243.6-093557 |
| 3          | 03 32 47.00   | −09 28 23.5   | 67 ± 8             | ...         |
| 4          | 03 32 48.87   | −09 27 11.5   | 53 ± 8             | ...         |
| 5          | 03 32 49.36   | −09 28 16.7   | 269 ± 9            | ...         |
| 6          | 03 32 54.99   | −09 27 29.4   | 65 ± 4             | ε Eridani   |
| 7          | 03 32 55.17   | −09 28 31.1   | 177 ± 6            | ...         |
| 8          | 03 32 56.15   | −09 25 30.0   | 54 ± 10            | ...         |
| 9          | 03 32 58.03   | −09 24 13.6   | 283 ± 34           | ...         |
| 10         | 03 32 58.17   | −09 25 06.1   | 1309 ± 25          | ...         |
| 11         | 03 32 59.18   | −09 28 28.0   | 60 ± 8             | S5          |
| 12         | 03 32 59.90   | −09 27 50.8   | 124 ± 23           | ...         |
| 13         | 03 32 59.94   | −09 27 52.6   | 42 ± 7             | ...         |
| 14         | 03 33 08.77   | −09 28 09.8   | 291 ± 34           | ...         |
| 15         | 03 33 09.21   | −09 28 43.6   | 500 ± 45           | ...         |
| 16         | 03 33 10.66   | −09 28 57.5   | 647 ± 90           | ...         |

Notes.

a Positional errors are ~0′′.2.
b Corrected for the primary beam response.
c These two sources are far from the phase center, and its flux density is a crude estimate.

The total power per unit volume is obtained integrating over the frequency

\[ \epsilon_{\upmu} = 6.8 \times 10^{-38} Z^2 n_e n_i T^{-1/2} \]

\[ \times \int_0^\infty \exp(-h\nu/kT) \tilde{g}_\nu d\nu, \]

\[ = 1.415 \times 10^{-27} Z^2 n_e n_i T^{1/2} \tilde{g}_\nu, \]

where \( \tilde{g}_\nu \) is the frequency average of the velocity-average Gaunt factor, which is in the range 1.1–1.5. Choosing \( \tilde{g}_\nu = 1.2 \) gives a 20% accuracy (Rybicki & Lightman 1986).

The power per unit volume over a frequency range is given by

\[ \epsilon_{\upmu}^{\Delta\nu} = 1.42 \times 10^{-27} Z^2 n_e n_i T^{1/2} \tilde{g}_\nu (e^{-u_1} - e^{-u_2}), \]

where the normalized energy is \( u = h\nu/kT \). For an optically thin plasma at a constant temperature, the luminosity in a normalized energy range \( (u_1, u_2) \) is obtained by integrating the emissivity over the volume \( V \):

\[ L_{\Delta\nu} = \int_V \epsilon_{\upmu}^{\Delta\nu} dV = 1.42 \times 10^{-27} Z^2 T^{1/2} \tilde{g}_\nu \]

\[ \times (e^{-u_1} - e^{-u_2}) \int n_e n_i dV. \]

The X-ray luminosity of ε Eridani has been measured with XMM-Newton in the energy range \([E_1, E_2] = [0.2, 2] \) kev, with
values in the range \((1.5–1.68) \times 10^{28}\) erg s\(^{-1}\) (Poppenhaeger et al. 2010; Loyd et al. 2016). Let \(L_R\) be the luminosity in the frequency range \([\nu_1, \nu_2]\) = \([6, 43]\) GHz where the spectrum is flat. Then, from Equation (5), the ratio of the free–free luminosity in the X-ray range \(L_X\) and in the radio range \(L_R\) is given by

\[
\frac{L_X}{L_R} = \frac{e^{-\nu_2 / \alpha} - e^{-\nu_1 / \alpha}}{e^{-\nu_2 / \beta} - e^{-\nu_1 / \beta}} = 3.5 \times 10^5 - 7.7 \times 10^3, \tag{6}
\]

where the lower value corresponds to \(T = 2 \times 10^6\) K and the upper value corresponds to \(T = 3 \times 10^6\) K. These temperatures are similar to those measured by Schmitt et al. (1996) for the peak of the temperature distribution of the coronal material of \(\epsilon\) Eridani.

The observed radio luminosity in the range 6–43 GHz is given by

\[
L_R^{\text{observed}} = 4\pi D^2 \int_{6\text{GHz}}^{43\text{GHz}} S_\nu d\nu = 3.31 \times 10^{22} \text{ erg s}^{-1}, \tag{7}
\]

where \(D = 3.2\) pc is the distance to \(\epsilon\) Eridani. Then, this radio luminosity implies a free–free emission in X-rays of

\[
L_X = L_R^{\text{obs}} \times \frac{L_X}{L_R} = 1.16 \times 10^{28} - 2.57 \times 10^{28} \text{ erg s}^{-1}, \tag{8}
\]

for a temperature in the range \((2–3) \times 10^6\) K, in agreement with the observed X-ray luminosity observed by XMM-Newton. Therefore, the radio emission in the flat-spectrum region is consistent with free–free emission for this range of plasma temperature. Note that line X-ray emission is also important in hot plasmas (e.g., Mewe et al. 1985; see their Figure 1). Thus, the total X-ray emissivity should be larger than the continuum free–free emission calculated in this section.

There are at least two possible sources of the free–free emission: a magnetically confined corona and a stellar wind. In the following section we will discuss the case of the stellar wind.

### 4.2. Free–Free Emission from a Stellar Wind

In this section, we explore the possibility that the radio emission comes from a stellar wind. We calculate the emission of an isothermal, spherically symmetric, fully ionized wind that has a spectrum \(S_\nu \propto \nu^{0.6}\) at low frequencies and becomes optically thin at high frequencies, such that \(S_\nu \propto \nu^{-0.1}\) (e.g., Panagia & Felli 1975; hereafter PF75).

Since the stellar wind is always opaque inside a radius that decreases with increasing frequency, one can estimate the turnover frequency of the stellar wind spectrum with the condition that the free–free optical depth is unity at an impact parameter equal to the radius of the star \(R_\star\). The optical depth at a normalized impact parameter \(\xi = p/R_\star \geq 1\), where \(R_\star\) is the stellar radius, is given by Equation 4(a) of PF75:

\[
\tau(\xi) = \frac{\pi}{2\xi^3} n_e^2 R_\star \kappa(\nu),
\]

where \(n_e\) is the electron number density at \(R_\star\), and the opacity in the radio range is given by \(\kappa(\nu) = 8.436 \times 10^{-28} \left(\frac{\nu}{10\text{GHz}}\right)^{-2.1} \left(\frac{T_\nu}{10^4\text{K}}\right)^{-1.35} a(\nu, T_\nu)\), where \(T_\nu\) is the electron temperature and \(a(\nu, T_\nu)\) measures the deviation from the exact formula (Mezger & Henderson 1967). The electron number density is given by the mass continuity equation

\[
n_e = n_w V_w^2 (4\pi R_\star^2 \mu m_H),
\]

where \(M_w\) and \(V_w\) are the wind mass-loss rate and velocity, \(\mu = 1.2\) is the mean mass per electron, and \(m_H\) is the proton mass. Then, the turnover frequency of the stellar wind spectrum, given by the condition \(\tau(1) = 1\), is

\[
\frac{\nu_{\tau}}{10\text{GHz}} = 1.19 \left[\frac{R_\star}{0.74 R_\odot}\right]^{-1.42} \left[\frac{M_w}{10^{-11} M_\odot\text{yr}^{-1}}\right]^{0.95} \left[\frac{V_w}{650\text{ km s}^{-1}}\right]^{-0.95} \left[\frac{T_\nu}{10^6\text{K}}\right]^{-0.64}. \tag{9}
\]

Furthermore, the level of the optically thin emission can be estimated by evaluating the partially optically thick flux in Equation (24) of PF75 at \(\nu_{\tau}\) such that

\[
S_{\nu}^{\text{thin}} = 96 \mu\text{Jy} \left[\frac{R_\star}{0.74 R_\odot}\right]^{0.85} \left[\frac{M_w}{10^{-11} M_\odot\text{yr}^{-1}}\right]^{0.9} \left[\frac{V_w}{650\text{ km s}^{-1}}\right]^{-1.9} \left[\frac{T_\nu}{10^6\text{K}}\right]^{-0.29} \left[\frac{d}{3.2\text{ pc}}\right]^{-2} \left[\frac{\nu}{\nu_{\tau}}\right]^{-0.1}. \tag{10}
\]

This approximation has a percentage error <25% for \(\nu > 10\text{GHz}\).

Although these equations are useful, to make a better comparison with the observed radio emission, we obtain the wind spectrum by integrating numerically the transfer equation

\[
I_\nu(\xi) = I_\nu^0 \exp(-\tau) + B_\nu(T_\nu)(1 - \exp(-\tau)),
\]

where the first term \(I_\nu^0 \exp(-\tau)\), included only for impact parameters \(\xi \leq 1\), is the stellar specific intensity that is attenuated by the wind in front of it. The flux is obtained by integrating \(I_\nu(\xi)\) over the source solid angle, for frequencies in the partially optically thick regime to frequencies beyond the transition to the optically thin regime.\(^9\) We assume \(V_w = 650\text{ km s}^{-1}\), which corresponds to the escape speed of \(\epsilon\) Eridani that has a mass \(M_\star = 0.83 M_\odot\), a radius \(R_\star = 0.74 R_\odot\), and a temperature \(T_\star = 5100\text{ K}\) (e.g., Bonfanti et al. 2015). Fixing the wind speed leaves only two parameters to fit the spectrum: the wind mass-loss rate \(M_w\) and the temperature \(T_\nu\). We consider three wind models with different temperatures that have the observed level of optically thin emission: models A, B, and C have \(T_\nu = 10^6, 10^5, 10^4\text{K}\), respectively. The mass-loss rate \(M_w\) of each model is determined by the requirement of fitting the observed optically thin flux. Table 3 shows the temperatures, mass-loss rates, and turnover frequencies of these models. The turnover frequency increases with decreasing temperature (see Equation (1)).

Figure 3 shows the wind spectrum of models A, B, and C with red dot-dashed lines superimposed on the data points. One can see that models B and C do not fit the observed emission at 6 GHz because their turnover frequency is too high. Therefore, one requires a wind with an electron temperature \(T_\nu \sim 10^6\text{ K}\). The wind temperature of \(\epsilon\) Eridani could be better constrained by determining the turnover frequency, which should be at frequencies \(\nu < 6\text{GHz}\).

\(^8\) For simplicity, we assumed \(\alpha(\nu, T_\nu) = 1\), which has an error up to 20% for the range of parameters considered here.

\(^9\) For the numerical integration, we use the exact formula for \(\alpha(\nu, T_\nu)\).
As shown in Table 3, assuming a spherical wind, the mass-loss rate required to reproduce the observed optically thin radio emission of ε Eridani is $\dot{M}_w \sim 6.6 \times 10^{-11} M_{\odot} \text{yr}^{-1}$, similar to the upper limits found by Fichtinger et al. (2017) for four young main-sequence solar-type stars using VLA and ALMA observations. This mass-loss rate is 3300 times the solar value $\dot{M}_w = 2 \times 10^{-14} M_{\odot} \text{yr}^{-1}$, and 110 times larger than the value obtained by Wood et al. (2005) for ε Eridani using the atmospheric Lyα absorption method. Nevertheless, the Lyα absorption method is indirect since it measures the heated H I within the interaction region between the stellar wind and the local ISM. In contrast, if the observed radio continuum emission is bremsstrahlung radiation, it is produced directly by the ionized circumstellar gas. We note that models of winds from cool stars driven by Alfvén waves and turbulence by Cranmer & Saar (2011) predict much lower mass-loss rates of the order of $\sim 5 \times 10^{-14} M_{\odot} \text{yr}^{-1}$. Other authors have associated the energy of stellar flares with coronal mass ejections with different assumptions to obtain the stellar mass-loss rate (e.g., Osten & Wolk 2015; Odert et al. 2017). In particular, Odert et al. obtain a low mass-loss rate for ε Eridani consistent with the Lyα method. Nevertheless, Osten and Wolk obtain a mass-loss rate of the order of $4 \times 10^{-11} M_{\odot} \text{yr}^{-1}$ for the young solar analog EK Dra that is similar to our value for ε Eridani.

In addition, the large mass-loss rate we find could help explain the Faint Young Sun Paradox, in which the geological evidence shows that the Earth and Mars had a much warmer climate in the past (e.g., Feulner 2012). The solution proposed by Whitmire et al. (1995) is that the Sun was more massive and luminous in the past but lost its excess mass in a solar wind with a mass-loss rate $\sim 1000$ times the present solar mass-loss rate, as large as the value we infer for ε Eridani. If the mass-loss rate remains constant, ε Eridani would lose $\sim 0.2 M_{\odot}$ by the time it reaches the age of the Sun, although one expects a decrease in mass-loss rate with time (see, e.g., discussion of Fichtinger et al. 2017).

4.2.1. Coexistence of the Wind and Disk

A relevant question one could ask is, can this relatively powerful wind blow out the dust grains in the surrounding debris disk? To investigate this point, we will make a rough comparison between the attractive force of gravity and the repulsive force produced by the ram pressure of the wind, both acting on a dust grain.

The force of gravity will be given by

$$F_g = \frac{G M_w (4/3) \pi a^3 \rho_d}{d^2},$$

(12)

where $G$ is the gravitational constant, $a$ is the radius of the dust grain, $\rho_d$ is the mass density of the dust grain, and $d$ is the distance from the grain to the star. On the other hand, the force due to the wind will be given by

$$F_w = \frac{\dot{M}_w v_w \pi a^2}{4 \pi d^2},$$

(13)

\[10\] An electron temperature of $T_e \sim 10^6$ K is in the range of the values measured by Schmitt et al. (1996) for the coronal material of ε Eridani.
The ratio between these two forces is given by

$$\frac{F_g}{F_w} = \frac{16 \, GM \omega_0 \rho}{3 \, M_w v_w} \sim 180,$$

(14)

where we adopted the stellar and wind parameters of \( \epsilon \) Eridani discussed above and assumed \( \alpha = 135 \, \mu \text{m} \) (Backman et al. 2009) and \( \rho_w = 2 \, \text{g cm}^{-3} \) (Love et al. 1994). Thus, the gravitational force dominates, and the coexistence of a strong stellar wind with the debris disk is plausible. Other authors have studied the problem of dust survival in debris disks in more detail by including radiation pressure, the Poynting–Robertson drag, and the stellar wind pressure (e.g., Plavchan et al. 2005; Augereau & Beust 2006; Strubbe & Chiang 2006; Backman et al. 2009). In the case of strong stellar winds, this agent is more important for grain removal than radiation pressure and the Poynting–Robertson drag.

4.3. Other Emission Mechanisms

Bastian et al. (2018) found that the radio emission in the range [4, 12] GHz is quasi-steady since they did not find significant variability during the observations. They showed that the radio luminosity per unit frequency of \( \epsilon \) Eridani in the 4–8 GHz band is \( L_\nu \sim 10^{12} \text{erg s}^{-1} \text{Hz}^{-1} \), so the ratio is \( L_X/L_\nu \sim 10^{16.5} \text{Hz} \). This is higher than the expected ratio of soft X-rays and nonthermal radio spectral luminosity near 5 GHz for magnetically active stars, \( L_X/L_\nu \sim 10^{15.5} \text{Hz} \), known as the G"{u}del–Benz relation (e.g., G"{u}del et al. 1995). Thus, \( \epsilon \) Eridani is underluminous in the radio relative to active stars. Bastian et al. (2018) argued that, even though \( \epsilon \) Eridani is younger and more active than the Sun, nonthermal radio emission is not required to explain the quasi-steady radio emission. In fact, as shown in Table 1, there is no evidence of circular polarization with upper limits of 12%–50%. Detection of significant circular polarization (a few tens of percent) would favor a nonthermal gyrosynchrotron emission mechanism. Instead, Bastian et al. proposed that the radio emission could be produced by thermal coronal free–free emission\(^{12}\) and thermal gyroresonance emission. A combination of these two mechanisms could explain the observed flat radio spectrum: the coronal free–free emission would dominate at the lower frequencies, while the gyroresonance emission would dominate at the higher frequencies. We refer the reader to Bastian et al. (2018) for a detailed discussion of these mechanisms. We note that optically thin free–free emission from \( 10^5 \text{K} \) material (a stellar wind or magnetically confined corona) is a simple mechanism that accounts for the flat spectrum in the whole observed range.

5. Conclusions

Our main conclusions can be summarized as follows:

(1) Using the VLA, we detected 33.0 GHz emission associated with the nearby star \( \epsilon \) Eridani. The radio and stellar positions coincide within \( 0''07 \pm 0''05 \) and strongly favor the conclusion that the radio emission comes from the star and not from a proposed giant exoplanet with a semimajor axis of \( \sim 1'' \).

(2) The centimeter emission directly associated with \( \epsilon \) Eridani is remarkably flat, and we show that it can be interpreted as optically thin free–free emission. We also show that this emission can be due to a stellar wind with a mass-loss rate of order \( M_w \sim 6.6 \times 10^{-11} \text{M}_\odot \text{yr}^{-1} \). However, as discussed above, other mechanisms could also produce this emission, so additional observations are needed to establish its nature. For example, the detection of circular polarization or the appearance of nonthermal (that is, strongly negative) spectral indices or fast (in the scale of minutes) temporal variations will favor mechanisms other than optically thin free–free.

(3) Sensitive 10.0 GHz observations made with the VLA reveal the presence of 15 sources in the field, in addition to the one associated with \( \epsilon \) Eridani. Only one of the 10.0 GHz sources appears to be associated with one of the 1.1 mm continuum sources detected by Chavez-Dagostino et al. (2016).

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Facility: VLA

Software: CASA McMullin et al. (2007).

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\(^{12}\) This is consistent with our interpretation of the emission as free–free as discussed in Section 4.1.
