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POSSIBLE RADIO SPECTRAL INDICES FROM INHOMOGENEOUS FREE-FREE SOURCES

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RESUMEN

En algunas regiones de formación estelar se han encontrado fuentes de radio contínuo con índices espectrales muy negativos ($\alpha < -0.1$, donde el índice espectral α está definido por $S_\nu \propto \nu^\alpha$). En este artículo exploramos si estos índices negativos podrían ser producidos por fuentes de emisión libre-libre con distribuciones de densidad y temperatura *ad hoc*. Encontramos que siempre que el mecanismo de emisión y absorción sea únicamente libre-libre, se obtendrá $\alpha \geq -0.1$ independientemente de las características de la fuente. Finalmente, exploramos la posibilidad de que los índices altamente negativos pudieran deberse a un efecto de absorción por polvo asociado a las regiones de formación estelar. Debido a las densidades columnares tan elevadas que ello requiere, parecería más natural admitir que los índices espectrales muy negativos hallados en estas fuentes peculiares se deben a radiación sincrotrónica ópticamente delgada.

ABSTRACT

Radio sources with large negative indices ($\alpha < -0.1$, where the spectral index α is defined by $S_\nu \propto \nu^\alpha$) have been found in regions of star formation. In this paper, we explore whether these spectral indices could be obtained from sources of free-free emission with *ad hoc* electron density and temperature distributions. We find that, if only free-free emission and absorption are involved, the spectral index will always be $\alpha \geq -0.1$ regardless of the source characteristics. Finally, we explore the possibility that the large negative spectral indices could be produced by dust absorption. However, the very high column densities required lead us to conclude that the large negative indices found in these peculiar sources are more naturally explained in terms of optically thin synchrotron emission.

Key words: **H II REGIONS – RADIATION MECHANISM – RADIATIVE TRANSFER**

1. INTRODUCTION

The solution for the specific intensity of free-free diation from a plane-parallel, homogeneous slab ionized hydrogen is given in the radio frequencies (Rybicki & Lightman 1979):

$$I_\nu^{ff} = \frac{2kT_e\nu^2}{c^2}(1 - e^{-\tau_\nu^{ff}}), \qquad (1)$$

here k is Boltzmann's constant, T_e is the electron mperature, ν is the observing frequency, c is the eed of light and τ_ν^{ff} is the optical depth of the slab.

The specific intensity given by equation (1) is valid under the assumptions that the source function of the free-free emission equals Planck's function at the electron temperature T_e and frequency ν and that we can use the Rayleigh-Jeans approximation. Both are good assumptions in the radio wavelengths, where we can also assume that the optical depth depends on frequency as $\nu^{-2.1}$ (Mezger & Henderson 1967). Then, for the limiting cases of small τ_ν^{ff} (large ν) and large τ_ν^{ff} (small ν) we obtain the well known behaviors of $I_\nu^{ff} \propto \nu^2$ (optically-thick limit) and $I_\nu^{ff} \propto \nu^{-0.1}$ (optically thin limit). Defining the spectral index α as $I_\nu \propto \nu^\alpha$, we can conclude that in the plane-parallel, homogeneous case we obtain values of α in the range from -0.1 to $+2$.

The main objective of this paper is to discuss whether spectral indices outside of the -0.1 to $+2$ range can be produced by free-free sources

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which are inhomogeneous both in electron density and temperature. The astrophysical motivation for this work is that, recently, several radio continuum sources with large negative indices (i. e., $\alpha < -0.1$) have been found in star-forming regions (de Muizon et al. 1988; Rodríguez et al. 1989; Yusef-Zadeh et al. 1989; Martí, Rodríguez, & Reipurth 1993; Curiel et al. 1993; Garay et al. 1993). These large negative spectral indices are most naturally explained as caused by optically thin synchrotron emission. This interpretation is confirmed when linear polarization can be detected. However, some of the sources with steep negative spectral indices are too weak to measure linear polarization in them. In addition the production of relativistic electrons in the physical conditions that characterize star formation is not easy to explain (Rodríguez et al. 1989). Then, it seems worthwhile to consider whether *ad hoc* free-free sources could give rise to large negative values of α.

Another possible explanation will also be considered, that is, the possibility that large negative spectral indices could be produced because of the absorption by large amounts of foreground dust. If the line of sight between a free-free emitting source and the observer contains a sufficiently high column density of absorbing dust, a radio spectral index as negative as required can be produced at least in a finite frequency range. The main reason why this mechanism works is that, at these wavelengths, the dust opacity increases with the frequency. Finally, an application is made to the apparently nonthermal radio sources found by Schwartz, Frerking, & Smith (1985) in the L1455 region.

2. FREE-FREE EMISSION FROM INHOMOGENEOUS SOURCES

2.1. *Semi-infinite, Plane-parallel, Inhomogeneous, Free-free Sources*

Let us consider the simple case of a semi-infinite, plane-parallel, free-free emitting source with an arbitrary power law dependence for its electron density and temperature given by:

$$n_e = n_0 (r/r_0)^m \tag{2}$$

and

$$T_e = T_0 (r/r_0)^n, \tag{3}$$

where m and n are the respective power law indices, while n_0 and T_0 represent the values of the density and temperature at the inner boundary of the source, located at $r = r_0$. If the source is semi-infinite, then m must be < -1 in order to have a finite column density.

The free-free absorption coefficient is given by (Rybicki & Lightman 1979):

$$\kappa_\nu^{ff} = 0.018\; n_e^2\; T_e^{-3/2} \nu^{-2} g(\nu, T_e), \tag{4}$$

where $g(\nu, T_e)$ is the Gaunt factor and cgs units are used throughout. A suitable form in the radio wavelengths can be expressed as:

$$g(\nu, T_e) = \frac{3^{1/2}}{2\pi}(ln\frac{T^3}{\nu^2} + 35.4). \tag{5}$$

In order to carry out an analytical discussion of the possible spectral indices, the free-free absorption coefficient will be approximated here by the power law formula of Mezger & Henderson (1967):

$$\kappa_\nu^{ff} = 0.212\; n_e^2\; T_e^{-1.35} \nu^{-2.1}. \tag{6}$$

This approximation is equivalent to assuming that the Gaunt factor has a frequency dependence as $\nu^{-0.1}$. This assumption is reasonable since, for the range of frequencies from 10^7 to 10^{12} Hz and an electron temperature of 10^4 K, the power law index of the Gaunt factor is always between -0.07 and -0.26. In particular at centimeter wavelengths, where most of the relevant continuum observations are made, this power law index is always very close to -0.1.

Defining a new non dimensional variable, $x \equiv r/r_0$, and substituting equations (2) and (3) in (6), the free-free optical depth from any point x to infinity can be written as:

$$\tau_\nu^{ff}(x) = \int_r^\infty \kappa_\nu dr = \frac{\kappa_0 r_0}{\gamma} \nu^{-2.1} x^{-\gamma}, \tag{7}$$

where we have introduced the constant

$$\kappa_0 \equiv 0.212\, n_0^2\, T_0^{-1.35}$$

and the exponent

$$\gamma \equiv 1.35n - 2m - 1.$$

Note that only values of $\gamma > 0$ are acceptable in order that the optical depth remains finite.

Furthermore, if LTE is assumed, the source function for free-free radiation S_ν equals the Planck function at the local temperature. In the Rayleigh-Jeans approximation,

$$S_\nu(x) = B_\nu(T_e(x)) \simeq (2kT_0\nu^2/c^2) x^n.$$

Also, from equation (7) we can express x as a unction of τ_ν^{ff}. Then, using the standard solution of radiative transfer,

$$I_\nu = \int S_\nu(\tau_\nu) e^{-\tau_\nu} d\tau_\nu,$$

ve get:

$$I_\nu^{ff} = \frac{2kT_0}{c^2}\left(\frac{\kappa_0 r_0}{\gamma}\right)^{n/\gamma} \nu^{2-2.1n/\gamma} \times$$

$$\times \int_0^{\frac{\kappa_0 r_0}{\gamma}\nu^{-2.1}} \tau_\nu^{-n/\gamma} e^{-\tau_\nu} d\tau_\nu. \qquad (8)$$

In the optically thin case the exponential in equation (8) approaches unity and the integral is elementary. It can be easily shown that this leads o the expected dependence $I_\nu^{ff} \propto \nu^{-0.1}$. On the contrary, in the optically thick case, the integral ends to be independent of ν as it approaches its imit $\Gamma(1 - n/\gamma)$. Then the specific intensity has the imple dependence $I_\nu^{ff} \propto \nu^{\alpha_{thick}}$, where:

$$\alpha_{thick} = 2 - 2.1\frac{n}{\gamma}. \qquad (9)$$

The spectral index α_{thick} can reach positive values as high as required by keeping n <0 and choosing m such that γ tends to +0. The negative values of α_{thick} are completely excluded because of he previous conditions $m < -1$ and γ >0.

2.2. *Semi-infinite, Plane parallel, Isothermal, Free-free Sources*

In the case of an isothermal source, $n = 0$, an optically thick spectral index of +2 is expected from equation (9). However, even when $n = 0$, t is possible to obtain highly positive spectral ndices provided that background emission with an appropriate brightness temperature T_{bg} is present. Then, the observed specific intensity turns out to be:

$$I_\nu^{ff} = \frac{2k\nu^2}{c^2}\left(T_{bg} e^{-\tau_\nu^{ff}} + T_e(1 - e^{-\tau_\nu^{ff}})\right), \qquad (10)$$

and the spectral index $\alpha = d\ln I_\nu^{ff}/d\ln\nu$ will be given by:

$$\alpha = 2 + \frac{2.1\tau_\nu^{ff}(T_{bg}/T_e - 1)}{(T_{bg}/T_e - 1) + e^{\tau_\nu^{ff}}}. \qquad (11)$$

For example, for $T_{bg}/T_e = 10$ (see Figure 1), the maximum value of α is 4.3 when $\tau_\nu = 2.1$, and it can be made an arbitrarily large positive number by increasing T_{bg}/T_e. In contrast, decreasing T_{bg}/T_e will give, as lowest possible value, $\alpha = -0.1$. To illustrate this graphically, we also show in Fig. 1 the case $T_{bg}/T_e = 10^{-4}$. For this case, the intensity flattens but α never falls below -0.1. We can generalize this result to an arbitrary number of slabs and find that for an arbitrary temperature profile, α can never drop below -0.1.

2.3. *Infinite Spherical Envelopes with Free-free Emission*

An infinite spherical envelope with constant electron temperature and electron density depending on radius as in equation (2) is perhaps the best studied case of free-free emission from an inhomogeneous source (i.e., Panagia & Felli 1975). The flux density of such a source has a spectral index given by:

$$\alpha = 2 + \frac{4.2}{(2m+1)}. \qquad (12)$$

Since this solution is valid only for $m \leq -3/2$ (otherwise the flux diverges), we find that α can go from values of -0.1 (as m goes to $-3/2$) to +2 (as m goes to $-\infty$). This range of possible values for α is the same of the plane-parallel, homogeneous slab case. When $m = -2$, the model $n_e \propto r^m$ describes a spherical wind of constant electron temperature, ionization fraction and velocity, and a value of $\alpha = +0.6$ is obtained.

The case of a wind with $n_e \propto r^{-2}$ and an electron temperature depending on radius as $T_e \propto r^n$ has been discussed by Chiuderi & Torricelli Ciamponi (1978), who find that the flux density of such source has a spectral index given by:

$$\alpha = \frac{(0.3 + 0.1n)}{(0.5 + 0.225n)}. \qquad (13)$$

Since this solution is valid only for $n \geq -1/0.45$ (otherwise the flux diverges), the spectral index can go from +0.44 to $+\infty$.

The case of a collimated outflow has been discussed by Schmid-Burgk (1982), who shows that the spectral dependence in frequency equals that of the corresponding spherical source.

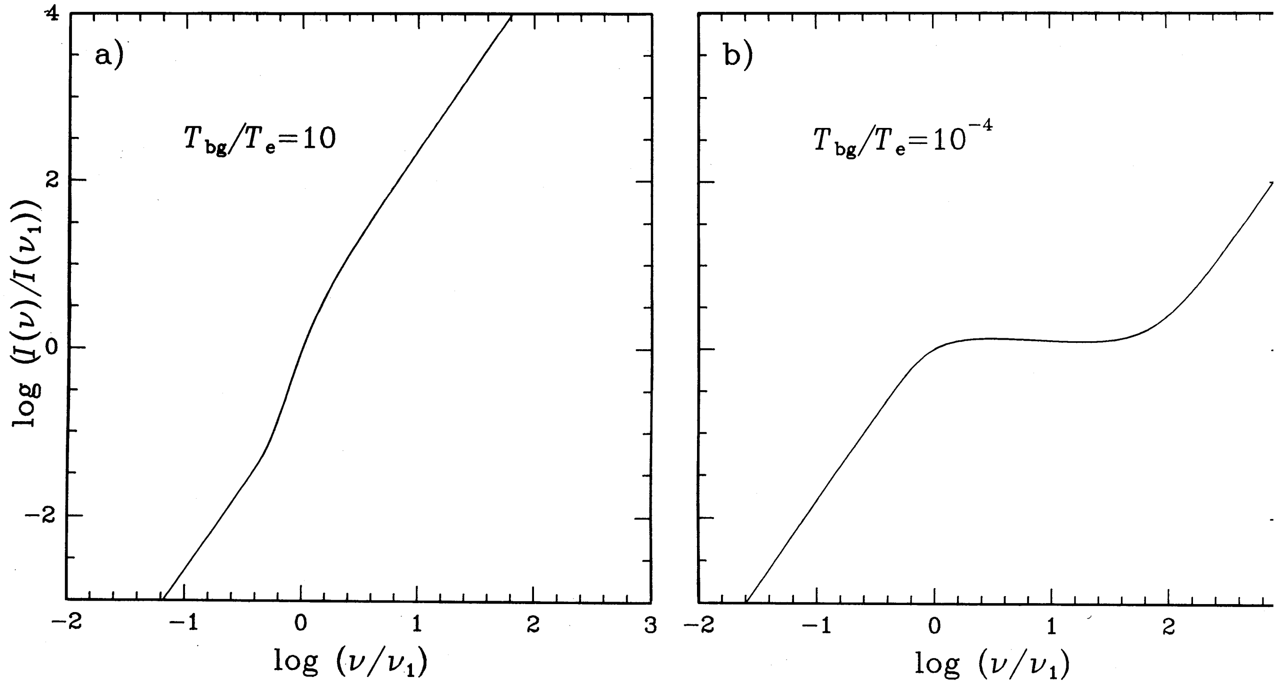

Fig. 1. *a*) Spectrum of a semi-infinite, plane-parallel, isothermal free-free source with electron temperature T_e and bacl ground thermal emission such that $T_{bg}/T_e = 10$. Axes units are normalized at values corresponding to optical depth unit *b*) The same as before with $T_{bg}/T_e = 10^{-4}$. Note that the spectral index never falls below -0.1.

3. A GENERAL ARGUMENT IMPLYING THAT ALWAYS $\alpha \geq -0.1$ IF ONLY FREE-FREE EMISSION IS INVOLVED

In the last section we have shown that even a simple configuration can give values of α larger than +2. However, we were not able to obtain values of α below -0.1. Is this a general property of free-free emission? In the next paragraph we present a general argument that implies that this is the case and that, regardless of the electron density and temperature distributions, $\alpha \geq -0.1$ as long as free-free radiation alone is considered.

Consider a differential element of length inside the emitting source that is located along the line of sight. The contribution of this element to the intensity will be proportional to $j_\nu^{ff} e^{-\tau_\nu}$, where j_ν^{ff} is the free-free emission coefficient that depends on frequency as $j_\nu^{ff} \propto \nu^{-0.1}$ and τ_ν^{ff} is the optical depth that depends on frequency as $\tau_\nu^{ff} \propto \nu^{-2.1}$. The contribution of this element of length will then have a spectral index $\alpha \geq -0.1$. But this conclusion is valid for any element of length, so we conclude that the intensity along a given line of sight will have $\alpha \geq -0.1$. Finally, the flux density will be the integral of the intensity over solid angle, but since the condition $\alpha \geq -0.1$ is valid for any line of sight, it will be valid also for the flux density. Then regardless of the electron density and temperature distributions, the condition $\alpha \geq -0.1$ is also valid for the flux density.

4. HIGHLY NEGATIVE SPECTRAL INDICES IN FREE-FREE RADIO SOURCES OBSERVED THROUGH DUST ABSORPTION

4.1. *An Overview of the Possible Mechanism*

Let us consider a simple homogeneous free-free radio source deeply obscured by a dust cloud along the line of sight. Assuming that dust emits thermally with a constant temperature T_d, the observed flux density taking into account both dust absorption and emission can be expressed as:

$$F_\nu = \frac{2k\Omega_s\nu^2}{c^2}\left[(T_e(1-e^{-\tau_\nu^{ff}})e^{-\tau_\nu^d} + \right.$$

$$\left. + \; T_d(1-e^{-\tau_\nu^d})\right] \;, \qquad (14)$$

with Ω_s being the solid angle subtended by the source and τ_ν^d the optical depth due to the dust.

In the normal conditions of the interstellar medium, τ_ν^d is usually neglected for centimeter wavelengths, and begins to be significant for submillimeter wavelengths. This means that if we wish the dust to produce some effect at centimeter wavelengths, where highly negative indices have been measured, some kind of unusual physical conditions are necessary.

At the present time there is great uncertainty about the dependence of dust opacity on frequency. Our lack of knowledge concerning the bulk composition of the nebular material, the particle size distribution and geometry, make it difficult to predict this dependence. The following power law expression (with two free parameters κ_0^d and β) is usually adopted for the specific dust absorption coefficient in millimeter radio astronomy (Beckwith et al. 1990), and we will assume that it can be extrapolated to the centimeter range:

$$\kappa_\nu^d = \kappa_0^d (\nu/\nu_0)^\beta . \quad (15)$$

Integrating equation (15) along the line of sight, the dust optical depth will be:

$$\tau_\nu^d = N\kappa_0^d (\nu/\nu_0)^\beta , \quad (16)$$

with N being the total mass column density of the dust cloud through which the free-free radio source is seen.

We can compute the spectral index by appropriate derivation of equation (14). Because we seek spectral predictions over a wide range of frequencies and temperatures, the expression of the free-free optical depth should include the Gaunt factor dependence:

$$\tau_\nu^{ff} = 0.018\ EM\ T_e^{-3/2} \nu^{-2} g(\nu, T_e), \quad (17)$$

being EM the electron measure for the homogeneous free-free radio source. On the other hand, for the dust optical depth, we take the frequency dependence $\tau_\nu^d \propto \nu^\beta$ already known from equation (16). The result found is:

$$\alpha = 2 + \{\beta\tau_\nu^d e^{-\tau_\nu^d}[T_d - T_e(1 - e^{-\tau_\nu^{ff}})] -$$

$$-2[1 + (ln\frac{T^3}{\nu^2} + 35.4)^{-1}]\tau_\nu^{ff} T_e exp-(\tau_\nu^{ff} + \tau_\nu^d)\} \times$$

$$\times [T_e(1 - e^{-\tau_\nu^{ff}})e^{-\tau_\nu^d} + T_d(1 - e^{-\tau_\nu^d})]^{-1} \ . \quad (18)$$

The spectral index predicted by equation (18) as a function of the observing frequency has been

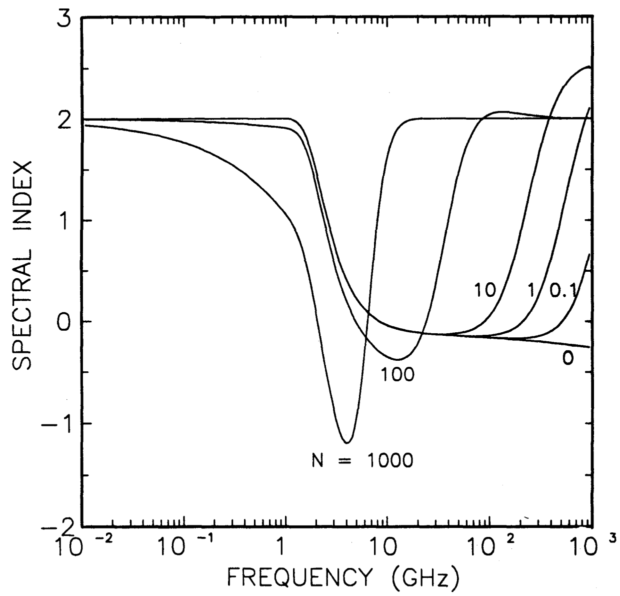

Fig. 2. Spectral index as a function of frequency for a free-free emitting source affected by absorption of dust in the line of sight. Note that, in the centimeter range, large negative spectral indices are obtained when the mass column density of the absorbing medium reaches values of $\sim 10^2$–10^3 g cm^{-2}. The following values for the dust and source parameters have been used: κ_0^d = 0.1 cm^2 g^{-1}, $\beta = 0.6$, $\nu_0 = 10^{12}$ Hz, $T_d = 20$ K, $T_e = 10^4$ K and $EM = 3 \times 10^7$ cm^{-6} pc.

plotted in Figure 2 for $\beta = 0.6$, $\kappa_0^d = 0.1$ cm^2 g^{-1}, $\nu_0 = 10^{12}$ Hz and different values of the mass column density N. For the model free-free radio source we have used fixed values of the electron measure ($EM = 3 \times 10^7$ cm^{-6} pc) and temperature ($T_e = 10^4$ K), while the adopted dust temperature was $T_d = 20$ K. Note that, as N is kept to low values, the spectral index changes only from +2 to about −0.1 as expected. Also, when one gradually increases N, α mantains the same behavior reaching again −0.1 but shortly afterwards the optically thin dust emission dominates and α tends towards the positive value β+2. Eventually, the dust emission becomes optically thick and the spectral index finally decreases towards +2 at very high frequencies. However, when the mass column density reaches values of $\sim 10^2$–10^3 g cm^{-2} or higher, the term $e^{-\tau_\nu^d}$ in equation (14) is able to deeply attenuate the free-free emission before the dust thermal emission becomes important. This attenuation produces a large negative spectral index in a frequency range several GHz wide for the highest values of N shown.

4.2. *Application to the Central Source of L1455*

L1455 is a dark molecular cloud where Schwartz et al. (1985) discovered a double radio source with an apparently nonthermal radio spectrum in both components. The object seems to be associated with a molecular flow and is almost coincident with the high density peak seen in NH_3 (1,1) emission (Anglada et al. 1989). These authors rule out the possibility that L1455 contains a luminous O star, but they also find it unlikely that the source could be an extragalactic background object because of the accurate angular coincidence of the flow and the radio double.

We consider here the possibility that this double source with nonthermal spectral index could be just two H II regions seen through anomalously large dust absorption. Hence, the presence of a couple of early type stars could still remain viable. The observations of Schwartz et al. (1985) were made using the VLA interferometer. As themselves point out, this kind of high resolution arrays tend to resolve out extended emission and to detect better the compact objects. In the framework of our dust explanation, this would imply that their spectra do not contain the extended thermal emission of dust. So, in the observed flux density given by equation (14) one has to drop the second term corresponding to the dust contribution. If one further assumes that, at all the frequencies, they observed optically thin free-free emission, this same equation reduces to:

$$F_\nu = \frac{2kT_e^{-0.38}}{c^2} 0.212\ EM\,\Omega_s \nu^{-0.1} e^{-N\kappa_0^d(\nu/\nu_0)^\beta} . \quad (19)$$

A fit of equation (19) to the spectrum of the central double radio source of L1455 gives the following values: $\beta = 0.61$, $EM\ R^2 T_e^{-0.38} = 1.05 \times 10^{54}$ cm^{-3} K$^{-0.38}$ and $N\kappa_0^d = 39.1$, where R is the radius of the H II region and the adopted distance to L1455 is 350 pc. The derived spectrum is represented in Figure 3 (continuous line). The unabsorbed theoretical spectrum (dashed line), with constant spectral index $\alpha = -0.1$, is also shown.

The low value of β found could be compatible with dust grains of the fractal type (Weintraub, Sandell, & Duncan 1991). On the other hand, even considering our lack of knowledge about κ_0^d, the value of the product $N\kappa_0^d$ obtained requires a very high mass column density N. For example, assuming a rather high estimate such as $\kappa_0^d = 0.1$ cm^2 g^{-1}, one needs $N \sim 400$ g cm^{-2}. This corresponds to hydrogen particle densities in the range 10^7–10^8 cm^{-3} for a region with linear sizes of 1–10 pc. For temperatures typical of the interstellar medium ($\sim$ 10–100 K), the Jeans mass of such a region is:

$$M_J \sim 10^{23} \rho^{-1/2} T^{3/2} \sim 1\ M_\odot, \quad (20)$$

being clearly smaller than its total mass, $M \sim 10^6\ M_\odot$. Therefore, the region would undergo gravitational collapse (Jeans 1902), making the dust absorption mechanism a rather untenable possibility. Then, one has to favor optically thin synchrotron radiation to account for the highly negative spectral indices observed. It should be noted, however, that the requirement of a very massive cloud between the radio source and the observer can be removed if the intervening medium is clumpy. In this case, the large obscuration could be provided by a small dense clump in the line of sight to the radio source.

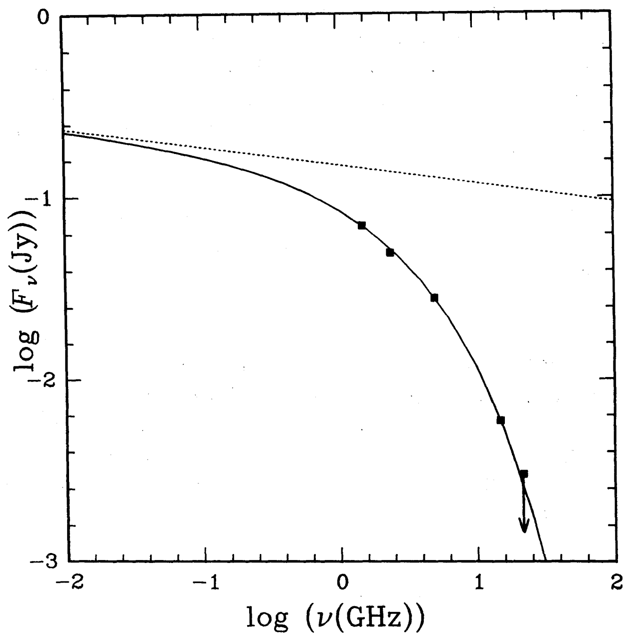

Fig. 3. Spectrum of the central double radio source found in L1455. The continuous line is a fit of equation (19) to the observed points. It represents an optically thin free-free emitting source deeply absorbed by dust located along the line of sight. The dashed line represents the unabsorbed theoretical spectrum, with $\alpha = -0.1$.

5. CONCLUSIONS

We discussed the possible radio continuum spectral indices from a free-free emitting source. We find that, when only the free-free emission and absorption mechanism is involved, the spectral index can be $\infty \geq \alpha \geq -0.1$ regardless of the electron density and temperature distribution. A source of free-free radiation alone cannot produce in the radio the arge negative spectral indices ($\alpha < -0.1$) observed in ome sources located in regions of star formation (de Muizon et al. 1988; Rodríguez et al. 1989; Yusef-Zadeh et al. 1989; Martí et al. 1993; Curiel et al. 1993; Garay et al. 1993).

An alternative explanation, different from the synchrotron mechanism, is considered by assuming hat highly negative spectral indices are the result of dust absorption at the observing frequencies. The double, apparently nonthermal radio source found in the L1455 dark molecular cloud is modeled from this point of view. However, we find that a very high column density of absorbing material, not usually found in the interestellar medium, is required. In addition, this extremely high column density will make the absorbing gas cloud unstable against gravitational collapse. Even when spectral indices well below -0.1 can be produced, the dust absorption possibility does not seem to be realistic. These peculiar sources with highly negative spectral indices are more naturally interpreted as optically thin synchrotron emitters.

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