THE WAVELENGTH DEPENDENCE OF SGR A* SIZE AND THE UNIFIED MODEL OF COMPACT RADIO SOURCES

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ABSTRACT

Using, in particular, the data upon Sgr A*, we propose the unified model of compact radio sources, i.e. of pulsars, maser sources, and active galactic nuclei. The unification is based on the wavelength dependence of radio source size. It is shown that the compact sources are characterized by a maser amplification of thermal radio emission. The density, temperature, and magnetic field profiles of compact sources are discussed. The wavelength dependence of Sgr A* size is explained by the effect of the gravitational field of a central energy source on a gas flow.

Subject headings: radiation mechanisms: thermal--AGN--pulsars--radio continuum
1. INTRODUCTION

The compact radio source at the Galactic Center, Sgr A*, was discovered as early as in 1971 (Lo 1982). In 1976 Davies, Walsh, and Booth have examined the wavelength dependence of Sgr A* size and inferred that the observed size of the source is proportional to $\lambda^2$, where $\lambda$ is the wavelength. The more later observations confirmed the $\lambda^2$ dependence of the source size at wavelengths of 2.8 cm to 30 cm (Lo 1982).

The observed size of Sgr A* is too large to suggest that the $\lambda^2$ dependence of the source size is produced by scattering of interstellar electrons (Lo et al. 1993). Here we show that the $\lambda^2$ dependence of the source size can be reproduced in the gaseous disk model with thermal emission, provided the effects of stimulated radiation processes are taken into account. This is the unified model of compact radio sources, Sgr A* being a representative of the family.

Compact radio sources have the small angular dimensions, usually less than 1 mas, and exhibit the high brightness temperatures. These properties are common for pulsars (Shklovsky 1984), masers (Bochkarev 1992), and active galactic nuclei (Bower & Backer 1998, Kellermann, Vermeulen, Zensus & Cohen 1998). The brightness temperatures of OH masers have the magnitude $T_b \leq 10^{12} K$, and those of water masers have the magnitude $T_b \leq 10^{15} K$ (Bochkarev 1992). Compact extragalactic sources (AGNs) exhibit brightness temperatures in the range of $10^{10} K$ to $10^{12} K$ (Bower & Backer 1998, Kellermann et al. 1998), so these temperatures have an order of magnitude of those of OH masers.

Another feature, which is common for the compact sources, is that their radio emission so far has not received a satisfactory explanation. In particular, it is true for pulsars (Qiao et al. 2000, Vivekanand 2002). In the case of maser sources the modern theory uses some chance coincidences which hardly can maintain in a more profound theory (Bochkarev 1992). At last, it was shown recently that spherical accretion models with the synchrotron mechanism of emission cannot explain the flat or slightly inverted radio spectra of low-luminosity active galactic nuclei (Nagar, Wilson & Falcke 2001, Ulvestad & Ho 2001). Besides, the synchrotron self-absorption produces a change in the polarization position angle across the spectral peak. No such a change was detected in gigahertz-peaked spectrum sources (Mutoh et al. 2002).
The difficulties encountered by plasma mechanisms of radio emission from pulsars clearly show that the radiation is produced by a dense, low-energy medium (Gedalin, Gruman & Melrose 2002). Such a medium is the gaseous disk surrounding the central energy source.

2. THE GASEOUS DISK MODEL

It was shown recently (Prigara 2001b) that thermal radio emission has a stimulated character. According to this conception thermal radio emission of non-uniform gas is produced by an ensemble of individual emitters. Each of these emitters is a molecular resonator the size of which has an order of magnitude of mean free path \( l \) of photons

\[
l = \frac{1}{n\sigma}
\]

(1)

where \( n \) is the number density of particles and \( \sigma \) is the photoabsorption cross-section.

The emission of each molecular resonator is coherent, with the wavelength

\[
\lambda = l,
\]

(2)

and thermal radio emission of gaseous layer is incoherent sum of radiation produced by individual emitters.

The condition (2) implies that the radiation with the wavelength \( \lambda \) is produced by the gaseous layer with the definite number density of particles \( n \). In the gaseous disk model, describing radio emitting gas nebulae (Prigara 2001a), the number density of particles decreases reciprocally with respect to the distance \( r \) from the energy center

\[
n \propto r^{-1}.
\]

(3)

Together with the condition of emission (2) the last equation leads to the wavelength dependence of radio source size:

\[
r_{\lambda} \propto \lambda.
\]

(4)

The relation (4) is indeed observed for sufficiently extended radio sources. For instance, the size of radio core of galaxy M31 is 3.5 arcmin at the frequency 408 MHz and 1 arcmin at the frequency 1407 MHz (Sharov 1982).

3. EXTENDED RADIO SOURCES
The spectral density of flux from an extended radio source is given by the formula

\[ F_\nu = \frac{1}{a^2} \int_0^a B_\nu(T) \times 2\pi r dr, \]  

(5)

where \( a \) is a distance from radio source to the detector of radiation, and the function \( B_\nu(T) \) is given by the Rayleigh-Jeans formula

\[ B_\nu = \frac{2kT}{\nu^2}, \]  

(6)

where \( \nu \) is the frequency of radiation, \( k \) is the Boltzmann constant, and \( T \) is the temperature.

The extended radio sources may be divided in two classes. Type 1 radio sources are characterized by a stationary convection in the gaseous disk with an approximately uniform distribution of the temperature \( T \approx \text{const} \) giving the spectrum

\[ F_\nu \approx \text{const}. \]  

(7)

Type 2 radio sources are characterized by outflows of gas with an approximately uniform distribution of gas pressure \( P = nkT \approx \text{const} \). In this case the equation (3) gives

\[ T \propto r, \]  

(8)

so the radio spectrum, according to the equation (5), has the form

\[ F_\nu \propto \nu^{-1}. \]  

(9)

Both classes include numerous galactic and extragalactic objects. In particular, edge-brightened supernova remnants (Kulkarni & Frail 1993) belong to the type 2 radio sources in accordance with the relation (8), whereas center-brightened supernova remnants belong to the type 1 radio sources.

The typical members of type 2 radio sources family are gigahertz-peaked spectrum sources (GPS), radio emission from GPS sources being produced by the expanding jets (Nagar et al. 2002).

The intermediate magnitudes of a spectral index \( 0 < \alpha < 1(\nu F_\nu \propto \nu^{-\alpha}) \) can be explained by the joint emission from an outflow (a jet) and a stationary gaseous disk.

4. THE WAVELENGTH DEPENDENCE OF RADIO SOURCE SIZE
In the case of compact radio sources instead of the relation (4) the relation
\[ r_\lambda \propto \lambda^2 \] (10)
is observed (Lo et al. 1993, Lo 1982). This relationship may be explained by the effect of a gravitational field on the motion of gas which changes the equation (3) for the equation
\[ n \propto r^{1/2} . \] (11)

The mass conservation in an outflow or inflow of gas gives \( nvr=\text{const} \), where \( v \) is the velocity of flow. In the gravitational field of a central energy source the energy conservation gives
\[ v = (v_0^2 + c^2 r_s / r)^{1/2} \] (12)
where \( r_s \) is the Schwarzschild radius. Therefore, at small values of the radius the equation (11) is valid, whereas at the larger radii we obtain the equation (3).

It is well known (Shklovsky 1984) that the delay of radio pulses from pulsars at low frequencies is proportional to \( \lambda^2 \). This fact is a mere consequence of Eq.(10), if we only assume the existence of the radial density wave traveling across the radius with a constant velocity and triggering the pulse radio emission. In this treatment the pulsars also obey the \( \lambda^2 \) dependence of compact source size. Note that the wavelength dependence of a pulse duration is a similar effect.

The spatial distribution of SiO, water, and OH masers (each of which emits in own wavelength) in the maser complexes also is consistent with the \( \lambda^2 \) dependence of compact source size (Bochkarev 1992, Eisner et al. 2001).

To summarize, extended radio sources are characterized by the relation (4), and compact radio sources obey the relation (10).

5. MASER AMPLIFICATION OF THERMAL RADIO EMISSION

The existence of maser sources associated with gas nebulae and galactic nuclei (Miyoshi et al. 1995) is closely connected with the stimulated origin of thermal radio emission. The induced origin of thermal radio emission follows from the relations between Einstein’s coefficients for a spontaneous and induced emission of radiation (Prigara 2001b).
The high brightness temperatures of compact, flat-spectrum radio sources (Bower & Backer 1998; Nagar, Wilson, & Falcke 2001; Ulvestad & Ho 2001) may be explained by a maser amplification of thermal radio emission. A maser mechanism of emission is supported by a rapid variability of total and polarized flux density on timescales less than 2 months (Bower et al. 2001). Such a variability is characteristic for non-saturated maser sources. Note that the spherical accretion models with the synchrotron mechanism of emission are unable to explain the flat or slightly inverted spectra of low-luminosity active galactic nuclei (Nagar et al. 2001; Ulvestad & Ho 2001). The Blandford and Königl theory used by Nagar et al. (2001) is in some respects similar to the gaseous disk model (Prigara 2001a), the latter being more simple and free from indefinite parameters, such as an empirical spectral index.

It is shown by Siodmiak & Tylenda (2001) that the standard theory of thermal radio emission which does not take into account the induced character of emission cannot explain the radio spectra of planetary nebulae at high frequencies without an introduction of indefinite parameters.

Thermal radiation in a magnetic field is polarized (see, e.g., Lang 1974). Together with the magnetic field profiles this produces the wavelength dependence of polarization in the form of $p \propto \lambda^{-1}$ for extended sources and $p \propto \lambda^{-2}$ for compact radio sources (Prigara 2002).

Maser amplification in continuum in different versions had been proposed earlier as possible radiation mechanism for pulsars (Lipunov 1987).

6. CONCLUSIONS

The compact radio sources are characterized by the following properties: 1) the small angular dimensions; 2) the high brightness temperatures; 3) the $\lambda^2$ dependence of radio source size; 4) the maser mechanism of radio emission.

Exactly by the maser mechanism of emission the compact radio sources differ from the extended ones, from the physical point of view.

The properties of the compact radio sources can be adequately described within the gaseous disk model with a suitable density profile.

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