INDUCED RADIO AND X-RAY EMISSION FROM AN ACCRETION DISK

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ABSTRACT. Radio and X-ray emission from compact sources with accretion disks (active galactic nuclei, pulsars and X-ray binaries) is considered. It is shown that both radio and X-ray emission from these sources can be interpreted as emission of a hot ($T \geq 3 \times 10^7 K$) plasma in the inner part of an accretion disk or in the disk corona. Radio emission is produced by the maser amplification of thermal radio emission in a hot plasma and corresponds to the transitions between highly located energy levels (somewhat similarly to the recombination lines). The X-ray emission is either thermal radiation from dense filaments or is produced by the coherent inverse Compton scattering of radio photons in the same dense filaments. The same mechanism, which gives rise to the maser amplification at radio wavelengths, produces also laser amplification in optical in X-ray binaries.

Key words: accretion, accretion disks—radiation mechanisms: general.

Introduction

In the unified model of compact radio sources, radio emission from active galactic nuclei (AGNs) and pulsars is treated as thermal radiation from an accretion disk amplified by a maser mechanism (Prigara, 2003a). A maser amplification of thermal radio emission in continuum produces the high brightness temperatures of compact radio sources and a rapid variability of total and polarized flux density, that is characteristic for non-saturated maser sources. In particular, pulsars signals show a variability on every observable time scale up to nanoseconds (Edwards&Stappers 2003, Vivekanand 2001). 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.

Maser amplification in continuum 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. However, the detailed mechanism of maser amplification has been unknown so far. In this paper we show that maser amplification is produced by the inversion of the high energy level population in a hot plasma.

The unified model of compact sources can be extended to account for emission in other bands. X-ray binaries have roughly two-component X-ray spectra with a thermal blackbody component and a power law spectrum (Falcke et al., 2003). The power law spectrum in the X-ray range has been also detected in some radio pulsars, X-ray pulsars and AGNs (Chakrabarty et al., 2001). The unified model predicts photon indices of the power law spectrum in the X-ray range which may be compared with the observed indices.

1. The gaseous disk model

It was shown recently (Prigara, 2003b) that thermal radio emission has a stimulated character. According to this conception thermal radio emission from non-uniform gas is produced by an ensemble of individual emitters. Each of these emitters is an elementary resonator the size of which has an order of magnitude of mean free path l of photons

$$l = \frac{1}{n\sigma} \tag{1}$$

where n is the number density of particles and σ is the absorption cross-section.

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

$$\lambda = l, \tag{2}$$

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 λ is produced by the gaseous layer with the definite number density of particles n .

The condition (2) is consistent with the experimental results by Looney and Brown on the excitation of plasma waves by electron beam (Chen, 1984; Alexeev, 2003). The wavelength of standing wave with the Langmuir frequency of oscillations depends on the density as predicted by equation (1). The discrete spectrum of oscillations is produced by the non-uniformity of plasma and the readjustment of the wavelength to the length of resonator. From the results of experiment by Looney and Brown the absorption cross-section for plasma can be evaluated.

The product of the wavelength by density is weakly increasing with the increase of density. This may imply the weak dependence of the size of elementary resonator in terms of the wavelength upon the density or, equivalently, wavelength.

In the gaseous disk model, describing radio emitting gas nebulae (Prigara, 2003a), the number density of particles decreases reciprocally with respect to the distance r from the energy center

$$n \propto r^{-1}. \tag{3}$$

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

$$r_\lambda \propto \lambda. \tag{4}$$

The relation (4) is indeed observed for sufficiently extended radio sources. For example, 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).

2. Radio emission from the gaseous disk

The spectral density of flux from an extended radio source is given by the formula

$$F_\nu = \frac{1}{a^2}\int_0^{r_\lambda} B_\nu(T) \times 2\pi r dr \quad , \tag{5}$$

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

$$B_\nu = 2kT\nu^2/c^2, \tag{6}$$

where ν 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 $T \approx const$ giving the spectrum

$$F_\nu \approx const \quad . \tag{7}$$

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

$$T \propto r, \tag{8}$$

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

$$F_\nu \propto \nu^{-1}. \tag{9}$$

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 relationship between linear size and turnover frequency in type 2 radio sources (gigahertz-peaked spectrum sources and steep-spectrum sources) (Nagar et al., 2002) is a consequence of the wavelength dependence of radio source size. The turnover frequency is determined by the equation $r_\nu = R$, where R is the radius of a gaseous disk. The same equation determines a turnover frequency for planetary nebulae (Prigara 2003a, Pottasch 1984, Siodmiak&Tylenda, 2001).

3. The unified model of compact radio sources

The unified model of compact radio sources (Prigara, 2003a) invokes an accretion disk with convection and outflows. The density profile $n \propto r^{-1/2}$used in the unified model is standard for an outflow or the convection dominated accretion flow (CDAF) models (Nagar et al., 2001). Here r is the distance from the central energy source. The temperature profile is virial, i.e. $T \propto r^{-1}$, only in active galactic nuclei (AGNs). In pulsars it has other forms. The fixed ratio of magnetic to gas pressure is inferred for AGNs, in pulsars the decouplement of magnetic and gas pressure is observed.

The unified model suggests the uniform maser amplification of thermal radio emission in continuum. In the model, the inferred brightness temperatures of radio pulsars are comparable to those of water vapor, OH and SiO masers. The unified model predicts the flat radio spectrum for a core emission from AGNs, the spectrum (9) for an outflow, and the intermediate ($0 < \alpha < 1$) values of the spectral indices for unresolved sources, depending on the relative contributions of an outflow and accretion disk. Here $F_\nu \propto \nu^{-\alpha}$is the flux density and is the frequency.

The model includes also radiation-induced solitary waves in an accretion disk to explain the phenomena seen in pulsars (Prigara, 2004).

In the case of compact radio sources instead of the relationship (4) the relationship

$$r_\lambda \propto \lambda^2 \tag{10}$$

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

$$n \propto r^{-1/2} \tag{11}$$

The mass conservation in an outflow or inflow of gas gives *nvr=const,* where v is the velocity of flow. In the gravitational field of a central energy source the energy conservation gives

$$v = \left(v_0^2 + c^2 r_s/r\right)^{1/2} \tag{12}$$

where r_s is the Schwarzschild radius. Therefore, at small values of the radius the equation (6) is valid, whereas at the larger radii we obtain the equation (3).

It is well known that the delay of radio pulses from pulsars at low frequencies is proportional to λ^2. This fact is a mere consequence of Eq.(10), if we only assume the existence of the radial density wave travelling across the radius with a constant velocity and triggering the pulse radio emission. In this treatment the pulsars also obey the λ^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 its own wavelength) in the maser complexes also is consistent with the λ^2 dependence of compact source size (Bochkarev, 1992; Eisner et al., 2002).

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

4. Maser amplification in compact radio sources

Recently, the energy distribution of atoms in the field of thermal black body radiation was obtained (Prigara, 2003b) in the form

$$N/N_0 = \sigma_a \omega^2 / \left(2\pi c^2\right) \left(exp\left(\hbar\omega/kT\right) - 1\right), \tag{13}$$

where N_0 is the population of the ground state E_0, N is the population of the energy level $E = E_0 + \hbar\omega$, σ_a is the absorption cross-section, $\hbar$ is the Planck constant, and T is the radiation temperature.

This distribution is valid in the range $\hbar\omega/kT \geq 1$, since in the limit $\hbar\omega/kT \rightarrow 0$ the line width is going to infinity, that indicates the violation of the one-particle approximation used by (Prigara, 2003b).

The function (13) has a maximum at $\hbar\omega_m = 1.6kT$. When the temperature exceeds the critical value of $T_0 = 3 \times 10^7 K$ (the inversion temperature), the population of the energy level E exceeds the population of the ground state E_0. Since the function (13) is increasing in the range $\omega < \omega_m$, the inversion of the energy level population is produced also in some vicinity of ω_m (below ω_m). This suggests the maser amplification of thermal radio emission in continuum by a hot plasma with the temperature exceeding the critical value T_0. Maser amplification in compact radio sources was assumed earlier by (Prigara, 2003a) based on the high brightness temperatures of AGNs. Since a hot plasma in an accretion disk is concentrated nearby the central energy source, maser amplification is characteristic for compact radio sources.

It is clear that, when the temperature of a plasma is below T_0, the radio flux is very small, and when the temperature exceeds T_0, radio emission is on. This an on-off cycle is detected in the radio pulsar PSR B1259-63 (Qiao et al., 2003). Similar is an on-off cycle in X-ray pulsars, e.g., the 35-day cycle in Her X-1. It implies that X-ray emission from X-ray pulsars is produced by the laser amplification in continuum which is quite analogues to maser amplification at radio wavelengths.

5. The photon indices of X-ray emission

X-ray binaries normally have the two most pronounced states (Falcke et al., 2003). The first one is the high/soft state dominated by the thermal blackbody emission from a thin disk. The second one is the low/hard state which is characterized by a dominant hard power-law spectrum whereas the thermal spectrum is weak or absent. The power-law spectrum is commonly attributed to an optically thin accretion flow or disk corona. However, there are other plausible origins of the power-law spectrum (Falcke et al., 2003).

The power-law spectrum in the X-ray range has also been detected in young classical pulsars, anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) (Chakrabarty et al., 2001). All these objects are believed to be isolated neutron stars. For AXPs and SGRs, the fallback accretion disk model has been proposed (Qiao et al., 2003). It is assumed that the accretion is fed by fallback material after the original supernova explosion.

To characterize the power-law spectrum, we introduce the photon index, Γ, defined such that photon number flux $dN/dE \propto E^{-\Gamma}$. Since $E = h\nu$, where h is the Planck constant, $\Gamma - 1$ is the spectral index in the X-ray range.

Classical young pulsars have power-law X-ray spectra with $\Gamma = 1.1 - 1.7$ in the 0.1-10 keV band, that corresponds to the spectral indices $\Gamma - 1 = 0.1 - 0.7$. Thus, the spectral indices for these pulsars lie between 0 and 1, similar to the spectral indices of radio emission from supernova remnants (SNRs).

The X-ray spectrum of most AXPs is best characterized by a two-component spectrum consisting of a ∼0.5 keV blackbody emission and a steep ($\Gamma = 3 - 4$) power law spectrum, with comparable luminosities in both components (Chakrabarty et al., 2001). The spectral indices for AXPs are in the same range, $2 < \Gamma - 1 < 3$, as the spectral indices of radio emission from pulsars . The latter can be inferred by making use of the density profile of compact radio sources, similarly to the spectra (7) and (8).

Active galactic nuclei (AGNs) typically lie within a range of photon indices $\Gamma = 1.2 - 2.2$, so the spectral indices $\Gamma - 1 = 0.2 - 1.2$ are close to those of classical young pulsars, i.e. lie in the same range as the spectral indices of radio emission from extended sources.

The theory of thermal emission from a gas with account for stimulated radiation processes gives the two possibilities to explain these values of photon indices in the X-ray range. The first one is to apply the above theory to the X-ray emission from a hot, optically thin in a classical sense disk corona. If the temperature of a gas is sufficiently high, then the Rayleigh-Jeans formula (6) is still valid, and the only difference with the radio band is the order of magnitude of the density, n, required by the equations (1) and (2) to produce X-ray emission. In this scheme, the power law spectrum can be produced either by the hot inner disk corona ($\Gamma = 3 - 4$) or by the hot filaments in the thick outer disk with outflows ($\Gamma = 1 - 2$).

Another possibility is the inverse Compton scattering of radio photons from an accretion disk by the hot disk corona or the hot filaments. However, the incoherent Compton scattering is not relevant in this case, because it does not conserves the spectral indices. In fact, the final spectrum is determined mostly by the spectral energy distribution of electrons and weakly depends upon the original radio spectrum. We should assume, instead, the coherent Compton scattering to reproduce the original spectral indices of radio emission (cf. Rees, 1982). It is plausible, that both these processes, the emission of thermal radiation and the inverse Compton scattering, contribute to the observed spectra.

The coherent inverse Compton scattering of radio photons from an accretion disk is supported by a strong (one-to-one) correlation between radio oscillation events and series of spectrally hard states in GRS 1915+105 (Klein-Wolt et al., 2002). Another observational evidence for the inverse Compton scattering in the hot disk corona is that the spectral indices of radio emission from X-ray binaries correspond to the emission from an outer disk. The radio emission from the inner part of an accretion disk, which has been detected in pulsars, in X-ray binaries is absent. It suggests that this emission is converted into X-ray emission via inverse Compton scattering.

Conclusions

In this paper, we elucidate the mechanism of maser amplification in compact radio sources, which has been suggested earlier based on the high brightness temperatures of these sources. Maser amplification is produced by the inversion of the high energy level population in a hot plasma.The inversion of the level population can produce also laser amplification in optical (e.g., the high variable shifts and intensities of the weak emission lines in Sco X-1 can be attributed to the weak laser sources) and X-ray bands. An on-off cycle in radio and X-ray pulsars may be explained by the periodic changes of the emitting gas temperature from higher to lower than the inversion temperature values.

The photon indices of the power law spectra in the X-ray range are obtained similar to the spectral indices of radio emission in the unified model of compact radio sources. The only difference is the higher density of an emitting gas. However, the detected correlation between radio and X-ray emission in X-ray sources suggests that another mechanism (the coherent inverse Compton scattering of radio photons) also contributes to the observed spectra.

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References

Alexeev B.V.: 2003, *Usp. Fiz. Nauk*, **173**, 145, *Physics-Uspekhi*, **46**, 139.

Bochkarev N.G.: 1992, *Basic Physics of Interstellar Medium*, Moscow University Press.

Bower G.C. & Backer D.C.: 1998, *ApJ*, **507**, L117.

Chakrabarty D., Pivovaroff M.J., Hernquist L.E., Heyl J.S. & Narayan R.: 2001, *ApJ*, **548**, 800.

Chen F.F.: 1984, Introduction to Plasma Physics and Controlled Fusion, **Vol. 1**, *Plasma Physics*, New York: Plenum Press.

Edwards R.T. & Stappers B.W.: 2003, *A&A*, **407**, 273.

Eisner J.A., Greenhill L.J., Herrnstein J.R., Moran J.M. & Menten K.M.: 2002, *ApJ*, **569**, 334.

Falcke H., Koerding E. & Markoff S.: 2003, *A&A*, **414**, 895.

Kellermann K.I., Vermeulen R.C., Zensus J.A. & Cohen M.H.: 1998,*AJ*, **115**, 1295.

Klein-Wolt M., Fender R.P., Pooley G.C., Belloni T., Migliari S., Morgan E.H. & van der Klis M.: 2002, *MNRAS*, **331**, 745.

Kulkarni S.R. & Frail D.A.: 1993, *Nature*, **365**, 33.

Lo K.Y.: 1982, in *AIP Proc. 83: The Galactic Center*, ed. G.Riegler & R.Blandford, New York.

Lo K.Y., Backer D.C., Kellermann K.I., Reid M., Zhao J.H., Goss M.H. & Moran J.M.: 1993, *Nature*, **361**, 38.

Nagar N.M., Wilson A.S. & Falcke H.: 2001, *ApJ*, **559**, L87.

Nagar N.M., Wilson A.S., Falcke H., Ulvestad J.S. & Mundell C.G.: 2002, in *Issues in Unification of AGNs, ASP Conf. Series 258*, ed. R.Maiolino, A.Marconi & N.Nagar, San Francisco.

Pottasch S.R.: 1984, *Planetary Nebulae*, Dordrecht: D.Reidel Reinhold Company.

Prigara F.V.: 2003a, *Astron. Nachr.*, **Vol. 324**, No. S1, Supplement: Proceedings of the Galactic Center Workshop 2002 – The central 300 parsecs of the Milky Way, ed. A.Cotera, H.Falcke, T.R.Geballe & S.Markoff, p.425.

Prigara F.V.: 2003b, *Int. J. Mod. Phys. D (submitted)*, astro-ph/0311532.

Prigara F.V.: 2004, *Phys. Plasmas (submitted)*, physics/0404087.

Rees M.J.: 1982, in *AIP Proc. 83: The Galactic Center*, ed. G.Riegler & R.Blandford, New York.

Qiao G.J., Xue X.Q., Xu R.X., Wang H.G. & Xiao B.W.: 2003, *A&A*, **407**, L25.

Sharov A.S.: 1982, *The Andromeda Nebula*, Moscow: Nauka.

Siodmiak N. & Tylenda R.: 2001, *A&A*, **373**, 1032.

Vivekanand M.: 2001, *MNRAS*, **326**, L33.