Resonant Cyclotron Emission of Whistler Waves by a Modulated Electron Beam

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(Received 10 March 1999)

The first observations of whistlers excited spontaneously by a modulated electron beam through normal Doppler shifted resonance have been reported in a laboratory experiment. The excited waves are propagating opposite to the beam direction and their phase and group velocities are characteristic of beam-whistler resonant cyclotron coupling. These results should shed light on mechanisms of whistler waves excitation in space plasmas, either by artificial beams injected from spacecraft in the ionosphere and the magnetosphere or by fluxes of energetic particles present in many astrophysical and space phenomena.

PACS numbers: 52.40.Mj, 52.35.Hr, 94.20.Rr, 94.30.Tz

The interaction of an electron beam with electromagnetic waves in a magnetized plasma has been widely studied in laboratory. Waves were excited by beams through various instability processes [1–4], in the whistler frequency range ($\omega_{\rm lh} < \omega < \omega_c$, where $\omega_{\rm lh}$ and ω_c are the lower hybrid and the electron cyclotron frequencies, respectively) as well as near the harmonics of ω_c or around the electron plasma frequency ω_p. On the other hand, spontaneous emission of whistler waves by modulated electron beams through Cherenkov resonant interaction has been studied recently in laboratory [5–9]. Owing to the modulation of the beam current, electron bunches can spontaneously emit significative Cherenkov radiation as a result of the coherence between the electrons [10–14].

Nevertheless, no laboratory observations of spontaneous whistler radiation by beams through normal Doppler shifted resonance have been reported. This resonant mechanism, which has been actively investigated theoretically and owing to numerical simulations [12–19], is thought to play an important role in space and astrophysical plasmas. For example, cyclotron resonance interactions of waves with energetic particles are namely believed to create enhanced electron precipitation and VLF emissions in planetary magnetospheres [20] or to be involved in solar flares [21]. However, electromagnetic waves radiated by electron beams injected from satellites in the magnetospheric and ionospheric plasmas during active space experiments have been shown to result from Cherenkov resonant radiation only [22–25]; indeed, higher beam energy is required for significative Doppler resonant radiation under ionospheric conditions.

This Letter reports the first observation in laboratory of whistler waves radiated spontaneously by modulated beams through normal Doppler shifted resonance; the resonant beam-wave coupling is described by the condition $k_z(m) = (\omega + m\omega_c)/v_{bz}$, where k_z and v_{bz} are the parallel wave number and the parallel beam velocity ($m = 0, \pm 1, \pm 2, \ldots$). Two different whistler excitation mechanisms have already been evidenced in our laboratory experiment when injecting a thin modulated electron beam into the plasma parallel to the ambient magnetic field $\mathbf{B}_0$ [8,9]: the Cherenkov resonant process ($m = 0$) and the nonresonant transition radiation from the beam injection region. When the beam injection is oblique, whistler radiation through normal Doppler shifted resonance ($m = -1$) with the spiraling beam can also be observed. As already mentioned above, the role of narrow spectrum beam density modulation is of crucial importance in our experiment, as it allows one to avoid destructive interferences between whistlers radiated by beam electrons and to reveal resonant whistler radiation well above the noise level. On another hand, when the beam is not modulated or when the imposed modulation has a broadband spectrum, whistler noise is observed in a wide range of frequencies and wavelengths (e.g., [8,9,26]). However, above the whistler frequency range, significative electromagnetic emission could be detected at ω_c and its harmonics, owing to a filtering of broadband magnetic fluctuations by the ordered cyclotron motion of electrons (constructive interference) [26].

Whistlers are right-polarized electromagnetic waves with frequency ω and wave number $\mathbf{k}(k_z, k_\perp)$ verifying the dispersion relation [27],

$$\frac{c^2k^2}{\omega^2} \simeq -\frac{\omega_p^2}{\omega(\omega - \omega_c\cos\theta)},$$

in the cold plasma approximation and for a dense plasma ($1 < \omega_p/\omega_c < 30$ in our experiment); θ is the whistler propagation angle with respect to the magnetic field $\mathbf{B}_0$ directed along the z axis ($\mathbf{B}_0 = B_0\mathbf{z}$). Figure 1 shows the whistler index surface for $\omega > \omega_c/2$ and for different plasma densities n_p. The straight lines $k_z^{\rm Ch} \equiv k_z(m = 0) = \omega/v_{bz}$ and $k_z^{\rm D} \equiv |k_z(m = -1)| = (\omega_c - \omega)/v_{bz}$ represent the Cherenkov and the Doppler resonance conditions between the modulated electron beam and the wave, respectively [let us point out that $k_z(m = -1) < 0$]. In both cases, beam-whistler resonant coupling occurs

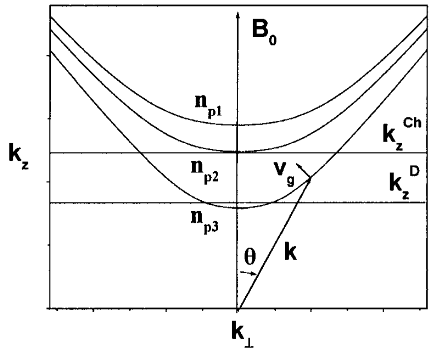

FIG. 1. Schematic representation of whistler waves index surfaces: variation of the parallel wave number k_z as a function of the perpendicular one, $k_\perp$, for $\omega > \omega_c/2$ and for different plasma densities $n_{p1} > n_{p2} > n_{p3}$ ($n_{p2} = n_p^{\mathrm{Ch}}$); the magnetic field $\mathbf{B}_0 = B_0\mathbf{z}$ is fixed; $k_z^{\mathrm{Ch}} = \omega/v_{bz}$ and $k_z^{\mathrm{D}} \equiv (\omega_c - \omega)/v_{bz}$ represent the Cherenkov and the Doppler resonance conditions between the modulated electron beam and the wave, respectively [to simplify the picture, we represent $k_z^{\mathrm{D}} = |k_z(m = -1)|$ instead of $k_z(m = -1) < 0$]; θ is the wave propagation angle with respect to $\mathbf{B}_0$ and $\mathbf{v}_g(v_{gz}, v_{g\perp})$, the whistler group velocity perpendicular to the index surfaces.

only for plasma densities lower than the plasma density thresholds n_p^{Ch} (for $m = 0$) and n_p^{D} (for $m = -1$); $n_p^{\mathrm{D}} \simeq n_p^{\mathrm{Ch}}(\omega_c/\omega - 1)^2$ for a dense plasma ($\omega_p \gg \omega_c$). When $\omega > \omega_c/2$, n_p^{Ch} is larger than n_p^{D}: for the plasma density domain $n_p^{\mathrm{D}} < n_p < n_p^{\mathrm{Ch}}$, only Cherenkov radiation can be observed; below the Doppler threshold n_p^{D}, both types of resonant emissions can occur. If $\omega < \omega_c/2$, n_p^{Ch} is smaller than n_p^{D}, and Doppler radiation can be observed in the domain $n_p^{\mathrm{Ch}} < n_p < n_p^{\mathrm{D}}$, where Cherenkov emission cannot appear. Whistlers excited through Doppler resonance propagate opposite to the beam direction: parallel group and phase velocities vectors, $\mathbf{v}_{gz}^{\mathrm{D}}$ and $\mathbf{v}_{pz}^{\mathrm{D}}$, verify $\mathbf{v}_{gz}^{\mathrm{D}} \cdot \mathbf{v}_{bz} < 0$ and $\mathbf{v}_{pz}^{\mathrm{D}} \cdot \mathbf{v}_{bz} < 0$, with $v_{pz}^{\mathrm{D}} = |\mathbf{v}_{pz}^{\mathrm{D}}| = \omega/k_z^{\mathrm{D}}$ and $\mathbf{v}_{bz} = v_{bz}\mathbf{z}$. On the contrary, Cherenkov radiation propagates in the beam direction ($\mathbf{v}_{gz}^{\mathrm{Ch}} \cdot \mathbf{v}_{bz} > 0$ and $\mathbf{v}_{pz}^{\mathrm{Ch}} \cdot \mathbf{v}_{bz} > 0$, with $v_{pz}^{\mathrm{Ch}} = |\mathbf{v}_{pz}^{\mathrm{Ch}}| = \omega/k_z^{\mathrm{Ch}}$).

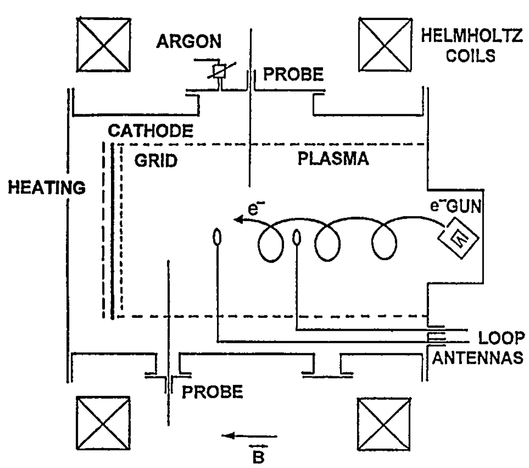

FIG. 2. Schematic view of the experimental setup.

The experiment (see Fig. 2) is performed in a discharge plasma (argon pressure between 10^{-5} and 10^{-3} Torr) generated by a large negatively biased oxide cathode that provides electrons accelerated by an adjacent grounded grid, which ionize the gas. The plasma (length of 0.7 m, radius of 0.3 m) is immersed in an axial and uniform magnetic field B_0 less than 300 G. Pulsed discharges are used and the experiment is performed in the afterglow Maxwellian plasma, where n_p and T_p (electronic temperature) vary in the ranges $[10^9, 10^{12}]$ cm^{-3} and $[0.1, 1]$ eV, respectively. The electron gun, which is a commercial available triode, is located in a separate chamber at the end of the main chamber opposite to the cathode. It consists of an oxide coated cathode, a grid of command used to modulate and regulate the electron beam as well as an acceleration grid. The injection pitch angle is fixed to $\theta_p = 45°$. The gun produces a beam of radius $r_b = 5$ mm with a modulated current I_b, an energy E_b, and a modulation frequency f_m below 5 mA, 300 eV, and 150 MHz, respectively.

All wave measurements have been performed with shielded moving loop antennas located far from the beam injection and absorption regions (gun exit and back wall of the chamber, respectively), so that transition radiation phenomena do not perturb significantly resonant wave emissions [8]. The measured whistler wave field will be indicated by A_w throughout the text. As expected, no resonant whistler radiation has been observed in a dense plasma where $n_p > \max(n_p^{\mathrm{Ch}}, n_p^{\mathrm{D}})$. In the ranges of parameters used in our experiment, no significant whistler radiation through Doppler resonance ($m = -1$) has been observed at low modulation frequencies ($f_m < f_c/2, f_c = \omega_c/2\pi$), even for densities $n_p^{\mathrm{Ch}} < n_p < n_p^{\mathrm{D}}$; for $n_p < n_p^{\mathrm{Ch}} < n_p^{\mathrm{D}}$, only Cherenkov whistler radiation has been detected at low f_m. Nevertheless, for $f_m > f_c/2$, whistler resonant radiation at $m = -1$ has been observed as well as Cherenkov radiation; thus, our study is mainly devoted to this case.

Phase velocities ($v_{pz}^{\mathrm{Ch}}, v_{p\perp}^{\mathrm{Ch}}$) of whistlers radiated through Cherenkov resonance have been obtained from the measurements of wave fields $\langle A_w^{\mathrm{Ch}}(t)\rangle$ as a function of time, registered for different longitudinal and radial positions z and r of the receiving loop antenna, in the domain $n_p^{\mathrm{D}} < n_p < n_p^{\mathrm{Ch}}$, where resonant beam-whistler interaction occurs only for $m = 0$ [see Figs. 3(a) and 3(b)]. Waves propagate in the beam direction, and the measured phase velocity $v_{pz}^{\mathrm{Ch}} \simeq 7.4 \times 10^8$ cm s^{-1} is in good agreement with the independently measured beam parallel velocity $v_{bz} \simeq 7.6 \times 10^8$ cm s^{-1}; the perpendicular phase velocity $v_{p\perp}^{\mathrm{Ch}}$, of the order of 10^9 cm s^{-1} [see Fig. 3(b)], is also close to the theoretical value. Figures 3(c) and 3(d) show similar measurements performed in the domain $n_p < n_p^{\mathrm{D}} < n_p^{\mathrm{Ch}}$: one can see that whistlers propagate opposite to the beam direction as it is the

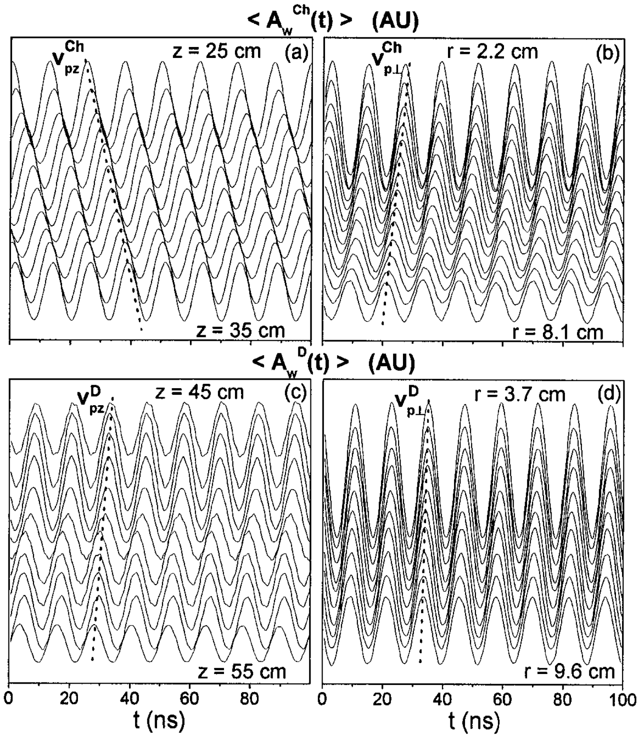

FIG. 3. Whistlers radiated through Cherenkov and Doppler resonances by a beam modulated at frequency f_m: (a) Variation of wave fields $\langle A_w^{\mathrm{Ch}}(t)\rangle$ as a function of the time t (Cherenkov emission), for different values of the longitudinal coordinate z along the ambient magnetic field ($z = 0$ is the position of the gun chamber exit and $25 < z < 35$ cm) which allows one to measure the parallel phase velocity $v_{pz}^{\mathrm{Ch}} \simeq 7.4 \times 10^8$ cm s^{-1}; (b) $\langle A_w^{\mathrm{Ch}}(t)\rangle$ for different radial positions r ($2.2 < r < 8.1$ cm), showing that $v_{p\perp}^{\mathrm{Ch}} \simeq 10^9$ cm s^{-1}; (c) variation of wave fields $\langle A_w^{\mathrm{D}}(t)\rangle$ as a function of the time t (Doppler emission), for different values of the longitudinal coordinate z along the ambient magnetic field ($45 < z < 55$ cm); the measured parallel phase velocity is $v_{pz}^{\mathrm{D}} \simeq 2.1 \times 10^9$ cm s^{-1}; (d) $\langle A_w^{\mathrm{D}}(t)\rangle$ for different radial positions r ($3.7 < r < 9.6$ cm), showing that $v_{p\perp}^{\mathrm{D}} \simeq 2.7 \times 10^9$ cm s^{-1}. Parameters are the following: $B_0 = 40$ G, $f_m = 81$ MHz, $v_{bz} \simeq 7.6 \times 10^8$ cm s^{-1}, $\theta_p \simeq 45°$, $n_p^{\mathrm{Ch}} \simeq 4.8 \times 10^{10}$ cm^{-3}, $n_p^{\mathrm{D}} \simeq 7 \times 10^9$ cm^{-3}; [(a),(b)] $n_p^{\mathrm{D}} < n_p \simeq 2 \times 10^{10}$ cm$^{-3} < n_p^{\mathrm{Ch}}$; [(c),(d)] $n_p \simeq 4 \times 10^9$ cm$^{-3} < n_p^{\mathrm{D}} < n_p^{\mathrm{Ch}}$.

case for resonant radiation at $m = -1$. Moreover, the corresponding phase velocities v_{pz}^{D} and $v_{p\perp}^{\mathrm{D}}$, of the order of 2.1×10^9 cm s^{-1} and 2.7×10^9 cm s^{-1}, respectively, are in accordance with phase velocities of whistlers excited through Doppler resonance. Let us mention that the resonant emission at $m = -1$ [Figs. 3(c) and 3(d)] is not significantly perturbed by the Cherenkov radiation which also occurs in this density domain, owing to an adequate choice of working parameters.

Figure 4 shows interferometric measurements of whistler waves radiated through resonant processes for different plasma densities; the measuring loop antenna was located at a radial distance $r = 3$ cm from the beam axis and was moved along z, between $z = 20$ and $z = 50$ cm ($z = 0$ is the position of the gun chamber exit). In order to simplify the interpretation of the curves, parameters have been chosen so that the parallel wavelengths $\lambda_z^{\mathrm{Ch}} = 2\pi/k_z^{\mathrm{Ch}}$ and $\lambda_z^{\mathrm{D}} = 2\pi/k_z^{\mathrm{D}}$ of whistlers excited through Cherenkov and Doppler resonances are very different. In the dense plasma ($n_p > n_p^{\mathrm{D}}$), only Cherenkov radiation is present (see upper curve of Fig. 4): the measured wavelength $\lambda_z^{\mathrm{Ch}} \simeq 2$ cm corresponds to the calculated value. When the plasma density decreases below n_p^{D}, radiation through Doppler resonance appears, characterized by a parallel wavelength $\lambda_z^{\mathrm{D}} \simeq 10.5$ cm, as expected (see lower curves of Fig. 4); beating between waves radiated by the beam through the different resonant processes occurs at $n_p < n_p^{\mathrm{D}} < n_p^{\mathrm{Ch}}$.

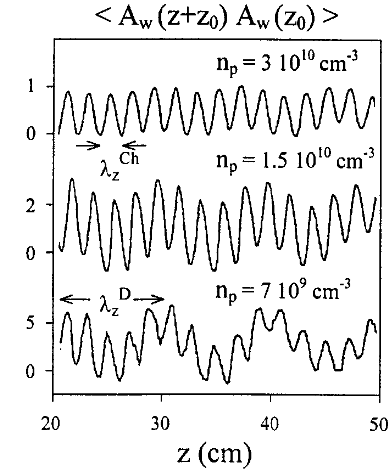

FIG. 4. Interferometric measurements of resonant whistler radiation at different plasma densities: $n_p^{\mathrm{Ch}} > n_p \simeq 3 \times 10^{10}$ cm$^{-3} > n_p^{\mathrm{D}}$ (upper curve); $n_p \simeq 1.5 \times 10^{10}$ cm$^{-3} \lesssim n_p^{\mathrm{D}}$ (middle curve); $n_p \simeq 7 \times 10^9$cm$^{-3} < n_p^{\mathrm{D}}$ (lower curve); λ_z^{Ch} and λ_z^{D} are the parallel wavelengths of whistlers excited through Cherenkov and Doppler resonances, respectively. Parameters are the following: $B_0 = 211$ G, $f_m = 500$ MHz, $n_p^{\mathrm{D}} \simeq 1.8 \times 10^{10}$ cm^{-3}, $n_p^{\mathrm{Ch}} \simeq 5.3 \times 10^{11}$ cm^{-3}, $v_{bz} \simeq 9.6 \times 10^8$ cm s^{-1}, $\theta_p \simeq 45°$; $\lambda_z^{\mathrm{Ch}} \simeq 2$ cm, and $\lambda_z^{\mathrm{D}} \simeq 10.5$ cm.

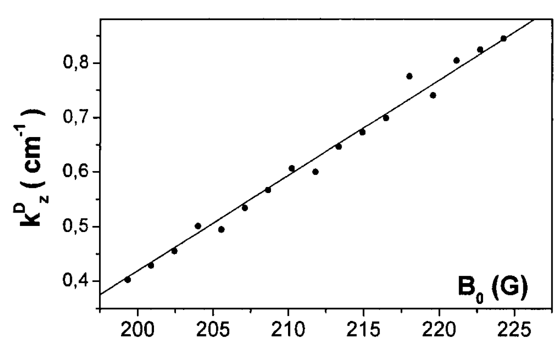

FIG. 5. Variation of the parallel wave number $k_z^{\mathrm{D}} = |k_z(m = -1)|$ (in cm^{-1}) of whistlers radiated through Doppler resonance as a function of the ambient magnetic field B_0, in gauss. Parameters are the following: $f_m = 500$ MHz, $n_p \simeq 5 \times 10^9$ cm^{-3}, $v_{bz} \simeq 9.6 \times 10^8$ cm s^{-1}, and $\theta_p \simeq 45°$.

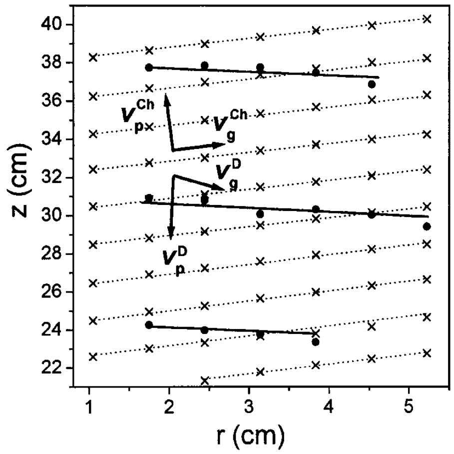

FIG. 6. Contours of constant phase (maxima and minima of axial interferometer traces) of whistlers excited through Cherenkov (dotted lines and crosses) and Doppler resonances (straight lines and dots). The horizontal and vertical axes represent the radial and the longitudinal coordinates r and z, respectively; $\mathbf{v}_g^{\mathrm{Ch}}$ and $\mathbf{v}_p^{\mathrm{Ch}}$ (respectively, $\mathbf{v}_g^{\mathrm{D}}$ and $\mathbf{v}_p^{\mathrm{D}}$) are the phase and group velocities of whistlers radiated at $m = 0$ (respectively, at $m = -1$). Parameters are the following: $B_0 = 205$ G, $f_m = 500$ MHz, $v_{bz} \simeq 9.6 \times 10^8\ \mathrm{cm\,s^{-1}}$, $\theta_p \simeq 45°$, $n_p \simeq 8 \times 10^9\ \mathrm{cm^{-3}}$, $n_p^{\mathrm{Ch}} \simeq 4.5 \times 10^{11}\ \mathrm{cm^{-3}}$, and $n_p^{\mathrm{D}} \simeq 10^{10}\ \mathrm{cm^{-3}}$.

Figure 5 presents the variation of the parallel wave number k_z^{D} of whistlers radiated through Doppler resonance as a function of the ambient magnetic field B_0, showing a linear dependence characteristic of resonant radiation at $m = -1$. The measured slope, $p = 0.015$, close to the calculated one ($p = 0.018$), can be used to measure the parallel beam velocity. Such a diagnostic could also be used for precise calibration of B_0.

Figure 6 shows contours of constant phase of whistlers resonantly excited by the beam through Cherenkov and Doppler resonances, in the plasma density domain $n_p \lesssim n_p^{\mathrm{D}} \ll n_p^{\mathrm{Ch}}$. As $n_p \ll n_p^{\mathrm{Ch}}$, oblique whistlers are radiated at $m = 0$ near the resonance cones direction (the resonance cone angle is $\theta_{\mathrm{res}} \simeq 23°$), as shown by measurements of the propagation angle $\theta^{\mathrm{Ch}} \simeq 25°$ (Fig. 6). Phase surfaces of Doppler radiation are characterized by a propagation angle $\theta^{\mathrm{D}} \simeq 13° < \theta_{\mathrm{res}}$. Directions of phase velocities $\mathbf{v}_p^{\mathrm{Ch}}$ and $\mathbf{v}_p^{\mathrm{D}}$ (normal to the phase surfaces) as well as of group velocities $\mathbf{v}_g^{\mathrm{Ch}}$ and $\mathbf{v}_g^{\mathrm{D}}$ (see Fig. 6) are determined taking into account that the perpendicular group velocity is directed outward the beam axis (at position $r = 0$).

In conclusion, first observations of whistlers excited spontaneously by a modulated electron beam through normal Doppler shifted resonance have been reported in a laboratory experiment. The excited waves are propagating opposite to the beam direction and their phase and group velocities are characteristic of beam-whistler resonant coupling at $m = -1$. These results should shed light on mechanisms of whistler wave excitation in space plasmas, either by artificial beams injected from spacecraft in the ionosphere and the magnetosphere or by fluxes of energetic particles present in many astrophysical and space phenomena.

The authors acknowledge the Centre National de la Recherche Scientifique (CNRS, France), the Ministère de l'Education Nationale, del'Enseignement Supérieur et de la Recherche (MENESR, France), the Russian Academy of Sciences, and the Russian Foundation for Basic Research (RFBR, Grant No. 98-02-17177) for their financial support.

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