Strong cosmic burst masers and the giant quantum generator model

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For the explanation of the nature of the radio-emission of strong cosmic burst H_2O masers we propose a new mechanism for the appearance of a generation regime; it is based upon the principle of the development of an absolute (global) wave instability in a three-dimensional nonequilibrium two-level quantum system. We give the conditions for generation and the Ginzburg–Landau type equation characterizing the radio-emission of masers in the generation regime. We note that in the case where a single-mode generator regime is realized one expects non-Gaussian statistics of the cosmic maser radiation and we explain, as in the single-mode regime, the strong dependence of the width of the line profile on the intensity which is observed for some strong cosmic burst H_2O masers.

1. INTRODUCTION

The observed narrow-band radio-emission of cosmic masers shows electromagnetic wave instabilities in a nonequilibrium cosmic molecular medium. Electromagnetic waves which vary in their statistical properties may develop in such nonequilibrium two-level quantum systems. As a result different radiative regimes can be realized, depending on the level of the inversion and other physical conditions.

The common theoretical approach for the construction of a model of cosmic masers is the travelling wave amplifier model. For a long time such an approach made it possible satisfactorily to describe the basic characteristics of the radio-emission of many of the observed maser sources.

However, recently with the development of radio-interference methods and the construction of very long baseline radio-interferometer systems which have a high resolution powerful burst H_2O masers were observed. The radio-emission of these strong cosmic masers showed new properties which differed markedly from the emission of previous H_2O masers. Attempts to explain them in the framework of the standard model of a cosmic maser as a travelling wave amplifier met with a number of practically insurmountable theoretical difficulties. This all indicates that the strong nonstationary radio-emission of nonequilibrium regions may be not only an interesting radiation because of its observational characteristics, but also, by all appearances, interesting and unique as regards the physical nature of the phenomenon. It is possible that these observations indicate the appearance of stationary and nonstationary cooperative coherent effects in a cosmic medium which is far from equilibrium. In this connection it seems appropriate to consider again the possibility of the emission of cosmic masers in the generation regime.

Lethokhov[1,2] was the first to consider a possible mechanism for the appearance of a generator radiation regime of cosmic masers in a nonequilibrium medium. The generation in Refs. 1 and 2 was determined by an inverse scattering process by the plasma, the dust, and the active molecules themselves (resonance scattering). In Refs. 1 and 2, and also in Ref. 3, which is a development of Refs. 1 and 2 for applications to lasers in stellar atmospheres, it is shown that the generator regime is attractive because if it is realized one does not need a large amplification when passing through an active nonequilibrium region and the growth of the intensity of the maser radiation occurs more efficiently. In particular, it was also noted in Refs. 1 and 2 that the use of the maser generator model makes it possible to explain the occurrence of strong radio-emission at low pumping levels, presupposes a stronger narrowing of the spectrum, and removes the limitations on the causes for the appearance of a variation in the radiation intensity. In Ref. 3 an important analysis was also given of the behavior of the width of the spectrum as a function of the radiation intensity for the case of single-mode generation due to the incoherent feedback in the case of resonance scattering by the active atoms (molecules) themselves.

However, when Refs. 1–3 appeared the astrophysicists had not yet observed a case of strong cosmic burst maser emission from nonequilibrium molecular clouds. The generator radiation regime therefore was not further developed or applied to an interpretation of cosmic maser radiation. In our opinion, the statement of the problem of a generator radiation regime in a nonequilibrium cosmic medium has again become urgent because of the observation of strong cosmic burst H_2O masers.[4–9]

We consider in the present paper a more general mechanism for the appearance of a generation regime in a nonequilibrium cosmic medium—as a transition from a convectively unstable amplification regime to an absolute (global) instability regime due to taking into account the spatial boundedness of the maser emission region and the differences in the dielectric characteristics of the medium inside and outside the source. We study the dynamics of the change in the radiation regime of a nonequilibrium medium from an incoherent noise (amplifier) regime to a cooperative, coherent regime. We determine some of the properties of the maser emission and its evolution in the generator regime indicating the reality of such a regime in the light of recent observational data.[4–9]

2. BASIC EQUATIONS

For a consistent analysis of possible radiation regimes of cosmic masers and their statistical properties we need study the self-consistent set of Maxwell equations for the electromagnetic field and the quantum equations for the

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density matrix of the active molecules. As a result the evolution of electromagnetic wave instabilities in a nonequilibrium two-level medium is determined by the following set of equations[10] for the electric and magnetic fields:

$$\mathrm{rot}\,\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t}, \qquad \mathrm{rot}\,\mathbf{H} = \frac{1}{c}\frac{\partial}{\partial t}(\mathbf{E}+4\pi\mathbf{P}) + \frac{4\pi}{c}\mathbf{J}, \tag{1}$$

and for the polarization density $\mathbf{P}$ and the population difference ΔN:

$$\frac{\partial^2 \mathbf{P}}{\partial t^2} + \frac{2}{T_2}\frac{\partial \mathbf{P}}{\partial t} + \left(\omega_0^2 + \frac{1}{T_2^2}\right)\mathbf{P} = \frac{\omega_c^2}{4\pi}\mathbf{E}, \tag{2}$$

$$\frac{\partial \Delta N}{\partial t} = \frac{\Delta N_0 - \Delta N}{T_1} + \frac{2}{\hbar\omega_0}\mathbf{E}\frac{\partial \mathbf{P}}{\partial t}. \tag{3}$$

Here $\mathbf{J}$ is the conduction current in the surrounding medium (the plasma, and so on) which takes into account the change in the dielectric permittivity and the presence of distributed dissipative processes in the surrounding medium, $\omega_c^2 = -8\pi d^2\Delta N\omega_0/3\hbar$ is the square of the cooperative frequency, T_1 and T_2 are the longitudinal and transverse relaxation times of the two-level system of active molecules, d is the quantum transition dipole moment, ΔN_0 is the population difference caused by the pumping and other relaxation processes, ω_0 is the resonance frequency, and c is the speed of light.

One must solve this system with boundary conditions determined by the continuity of the tangential components of the electric and magnetic fields and their derivatives on the boundary of the active molecular medium with a dielectric permittivity $\varepsilon_1(\omega)$ and the surrounding medium with $\varepsilon_2(\omega)$. When analyzing these equations we shall assume that the nonuniform broadening effects are small, i.e., we shall neglect spatial dispersion. These equations must also be supplemented with fluctuation (noise) terms caused by the various radiation processes in the active medium itself or in the surrounding space. The theory of cosmic masers in its most general form is thus given by equations describing physical processes in continuously distributed systems with fluctuations.

3. SELF-EXCITATION (GENERATION) OF RADIATION IN A NONEQUILIBRIUM BOUNDED COSMIC MEDIUM

Many studies of the set of equations given above have shown that in them various kinds of (convective and absolute) wave instabilities can develop and that these can produce the amplification and generation of electromagnetic waves. We consider here the appearance of an absolute (global) instability[11,12] in cosmic masers due to the difference in the dielectric characteristics of the active region and the surrounding space. Under cosmic maser conditions such a regime may arise when we take into account the boundaries of the active region and the difference between the dielectric characteristics of the emitting region and the surrounding space. The appearance of standing (eigen) waves in the medium due to the presence of boundaries and wave amplification produces conditions for a transition from an amplifier to a generator regime.

It is well known that in a bounded space the spectrum of the oscillations has a discrete structure. The boundary conditions for the values of the electric and magnetic fields and their derivatives at the boundary surface determine a discrete set of wave numbers. As a result the fields which arise are in the form of spatial harmonics and the active molecules interact strongly only with resonant harmonics and transfer their energy to those. One has then the growth of well defined modes, which depend on the boundary and physical conditions, and separated angular directions for the energy propagation are produced.

One can obtain exact or sufficiently simple analytical solutions for the spatial structure of the wave instabilities for a nonequilibrium medium with configurations which have the simplest geometry, such as a plane-parallel layer, a cylinder, or a sphere. For the analytical discussion of the possibility of the appearance of generation we therefore analyze it using the example of a maser source in the shape of a sphere of radius R. To solve the problem of the instability leading to the appearance of oscillations in a bounded nonequilibrium medium we need solve the set of Eqs. (1)–(3) for arbitrary initial conditions and appropriate boundary conditions. In the problem considered the boundary conditions will be nonuniform since the electromagnetic fields outside the nonequilibrium system also need to be determined. The boundary conditions reduce then in the given geometry (a sphere) to conditions for the continuity of the tangential components of the electric and the magnetic field and their derivatives for $r = R$. If we use the asymptotic solutions of the boundary value problem when the solutions inside the sphere are Bessel functions with half-odd-integral index n, and outside the sphere Hankel functions, the characteristic equation takes for $R \gg \lambda$ (λ is the wavelength of the maser radiation) the form

$$\mathrm{tg}\,(kR - \pi n/2) = i\phi, \tag{4}$$

where we have $\phi = \varepsilon_1^{1/2}(\omega)/\varepsilon_2^{1/2}(\omega)$ and $\phi = \varepsilon_2^{1/2}(\omega)/\varepsilon_1^{1/2}(\omega)$, respectively, for the electric and magnetic modes and the dielectric permittivity $\varepsilon_1(\omega)$ is defined as the sum of the dielectric permittivity of the surrounding medium $\varepsilon_2(\omega)$ and a contribution χ of the active molecules in the source:

$$\varepsilon_1(\omega) = \varepsilon_2(\omega) + 4\pi\chi = 1 + 4\pi i\sigma/\omega + 4\pi\chi.$$

As a result we obtain

$$k_m = \pi(n+2m)/2R - iq_m, \tag{5}$$

where $q_m = (c/R)\,\mathrm{artanh}\,\phi$ characterizes the nonuniformity of the field of the mode and determines the magnitude of the energy loss by the radiation through the surface of the sphere. The roots of Eq. (4) enable us to find the values of the wave numbers $k_m = k_m' + ik_m''$ in the bounded medium. The values of these roots enable us to determine the complex frequencies $\omega = \omega' + i\omega''$ from the dispersion equation

$$\omega^2\varepsilon_1(\omega) = \omega^2\left[1 + \frac{4\pi i\sigma}{\omega} - \frac{\omega_c^2}{(\omega + i/T_2)^2 - \omega_0^2}\right] = c^2k^2. \tag{6}$$

The solution of the characteristic equation (6) then determines the frequencies ω' and the value of the instability growth rate ω'' for which generation arises ($\omega'' > 0$):

$$\omega_m' \approx \omega_0 + \frac{1}{2}\frac{\omega_c^2\omega_0(1-\eta_m)}{[\omega_0^2(1-\eta_m)^2 + (4\pi\sigma + \omega_0\delta_m - 2T_2^{-1})^2]}, \tag{7}$$

$$\omega_m'' \approx -\frac{1}{T_2} - \frac{1}{2}\frac{\omega_c^2(4\pi\sigma + \omega_0\delta_m - 2T_2^{-1})}{[\omega_0^2(1-\eta_m)^2 + (4\pi\sigma + \omega_0\delta_m - 2T_2^{-1})^2]}. \tag{8}$$

Here we have

$$\eta_m = c^2 (k_m'^2 - k_m''^2)/\omega_0^2, \quad \delta_m = -2c^2 k_m' k_m''/\omega_0^2.$$

We have thus shown the conditions when the linearized set of Eqs. (1)–(3) becomes absolutely unstable and its wave solutions can increase without bounds with time. However, because of the nonlinearity of the system of initial equations (1)–(3) these solutions may leave the stationary regime. Qualitatively this follows already from the fact that increasing E leads [according to Eq. (3)] to a decrease (saturation) of ΔN and hence to a discontinuation of the growth of E.

The relations (7) and (8) which we have obtained are on the whole valid for any source geometry, if we assume that the values of η_m and δ_m are known for the given source geometry.

4. DYNAMICS OF THE GENERATOR RADIATION REGIME OF A NONEQUILIBRIUM COSMIC MASER MEDIUM

We have shown above that a nonequilibrium cosmic maser medium can change its radiation regime. It is clear that the dynamics (evolution) of the change in regime and of the radiation characteristics must also follow from the set of Eqs. (1)–(3) and we must thus be interested in such solutions for which the system described by (1)–(3) suddenly changes its properties and loses those that existed earlier, acquiring some qualitatively new characteristics. From that point of view the following will in all likelihood occur in the case considered by us. For small pumping levels when condition (8) is not yet satisfied and (or) there is no electrodynamic resonance [condition (7)] the fields connected with the emission by the molecules cannot be added coherently. In that case the fields of the radiation by separate molecules are added randomly and only the fluctuations, which are amplified through induction by the excited molecules, remain of these fields. On the other hand, in the case where conditions (7) and (8) are satisfied the fields are added in phase and the excited molecules interact coherently with these fields and emit cooperatively. From a mathematical point of view this can be expressed as follows: up to the appearance of generation in the framework of Eqs. (1)–(3) we have a solution with $\langle E \rangle \equiv \langle P \rangle = 0$. From the appearance of generation Eqs. (1)–(3) have regular solutions, i.e., $\langle E \rangle \neq 0$ and $\langle P \rangle \neq 0$.

The electromagnetic field, the polarization, and the population difference satisfy the nonlinear equations (1)–(3) which depend on the nonequilibrium parameters $(\Delta N_0, T_{1,2}, \sigma)$, and for well defined values of these parameters we have up to the appearance of the generation regime in the framework of these equations a solution of the form $\langle E \rangle \equiv \langle P \rangle = 0$. One can by appropriate methods show the existence and stability of such solutions which are damped waves. For other values of the parameters the wave solutions of these equations become unstable and growing. In the general case such solutions can be defined by a set of modes. The field resulting in reality is a superposition of these modes with the appropriate amplitudes. We can for these unknown mode amplitudes obtain a nonlinear equation which reminds us strongly of the equation from the theory of phase transitions.

Using standard methods[13,14] we can arrive near the first critical point of the set of Eqs. (1)–(3) at an equation for a single variable (the order parameter). Since near the critical point the solution of the form $\langle E \rangle \equiv \langle P \rangle = 0$ becomes unstable, all terms except a single variable, are relatively small and add only small corrections. As a result the structure arising there (the new solution) is near this point determined by the superposition of a finite number of spatial harmonics which are solutions of the Helmholtz equation

$$(\nabla^2 + k_m^2) U_m = 0, \tag{9}$$

where $U_m(\mathbf{r})$ describes the spatial structure of the maser field determined by the geometry and the boundary conditions. The structure of the finite solution $E(\mathbf{r},t)$ depends therefore both on the internal (dynamic) parameters and on the external (boundary) conditions.

Finally we can obtain the following nonlinear equation describing the slowly varying amplitude $\widetilde{E}(\mathbf{r},t)$ of the maser field, once the instability has occurred:

$$\frac{\partial E}{\partial t} = [\alpha - \beta |\widetilde{E}|^2 + \nu (k_0^2 + \nabla^2)^2] E, \tag{10}$$

where

$$\alpha = (2\pi\hbar\omega_0\mu^2\Delta N_0 - 8\pi\sigma T_2^{-1})/2(2\pi\sigma + T_2^{-1}),$$
$$\beta = 4\pi\sigma\mu^2/(2\pi\sigma + T_2^{-1}) T_1^{-1}, \quad \mu = 2d/\hbar,$$
$$\nu = -2\pi\sigma/2\omega_0^2 T_2 (2\pi\sigma + T_2^{-1})^3.$$

It follows from the form of this equation that it is similar to the Ginzburg–Landau equation and differs from the latter by the "diffusion" term. It is thus rather complicated for an analysis in three-dimensional space, like the Ginzburg–Landau equation, and one must expect[15] that Eq. (10) also predicts a very broad spectrum of processes—from the appearance of space-time coherent structures to various bifurcations, nonstationary pulses, and the development of chaos in three-dimensional space. We note that although such a generalized Ginzburg–Landau equation, obtained after the first instability (bifurcation), can describe also other processes, nonetheless when the degree of nonequilibrium increases Eq. (10) cannot sufficiently accurately reflect the dynamics of the wave instabilities. To do this we need go beyond the confines of the first critical region and consider a strongly nonlinear equation. It is also clear that to obtain a particular result we must use approximate methods or perform the appropriate calculations on a computer.

5. STATISTICAL AND SPECTRAL PROPERTIES OF THE EMISSION BY COSMIC MASERS IN THE GENERATION REGIME

To elucidate the problem of what are the consequences of the generator model of the emission we consider the problem of the statistical and spectral properties of the maser emission. The emission by a cosmic maser is, like most electrodynamic phenomena, a nonstationary random process. Not only the fluctuations in the phase, but also those in the amplitude of the maser emission are such processes. In a single-mode radiation regime when the different modes are statistically independent the statistics of the field of a cosmic maser must be Gaussian.[3]

However, if a single-mode stationary generation regime is realized in cosmic masers one can expect for the observations[1)] that the statistics of the radiation will differ from being Gaussian. Since just this case is the most interesting one as an indication of the actual occurrence of a cooperative coherent effect in the Universe and therefore will differ from all traditional noisy astrophysical sources we consider it in detail.

The simplest possibility for the occurrence of a single-mode stationary regime is the case when the pumping power is sufficient only for the generation of a single mode. In that case the realization of one of the solutions of spatial harmonics in (9) is possible and this is possible for the solution having the smallest threshold value of $\omega_m'' > 0$ in (8). Under well defined conditions the self-excitation of a single mode cannot make the occurrence of another form of spatial modes possible.[3]

Another possibility for the appearance of a single-mode regime is when the following condition is satisfied for the distance between the modes: $\Delta\omega \approx 1/T_2 < c/R$. If we bear in mind that the minimum value of T_2^{-1} is bounded by the natural broadening this is for H_2O masers (the 6_{16}–5_{23} transition) $\approx 10^{-9}\,s^{-1}$,[16] so that the value of the critical size R of the generation region can vary within rather reasonable limits from the point of view of the occurrence of the maser effect in interstellar clouds (10^{18} cm and less). However, it is clear that increasing the value of the uniform broadening dictates a decrease in the value of the possible radius of the generation region.

And, finally, a third case for the consideration of the single-mode regime may be connected with the observation of a single separate spatial mode since in the case of cosmic masers the spatial structure of the modes differs from one-dimensional radiation (laboratory lasers and masers). In the case of cosmic masers the emission takes place in different directions with a complex directivity diagram and (because of the complexity of the geometric structure of the source) it may happen that in the direction to the observer only one of the spatial modes dominates.

In the case of a single-mode regime one can give a simple analysis of the statistical and spectral properties of the maser radiation within the framework of Eq. (10). The evolution equation for a single spatial mode will then have the form

$$\frac{\partial \tilde{E}_m}{\partial t} = (\alpha_m - \beta_m |\tilde{E}_m|^2)\tilde{E}_m + \tilde{F}_m(r,t), \tag{11}$$

where $\tilde{F}_m(\mathbf{r},t)$ takes into account the existence of δ-correlated fluctuation processes in the source.

For an analysis of the statistical and spectral properties of the maser field we consider the corresponding Maxwell–Langevin Eq. (11) and the Fokker–Planck equation for the probability distribution for the field amplitude.[17] Expressing the complex amplitude in terms of the amplitude and phase variables, $\tilde{E} = E\exp(i\varphi)$, and assuming statistical independence of their fluctuations we can obtain the following equations for the distribution of the amplitude W of the maser field:

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial E_m}\left[\left(\alpha_m - \frac{D_E}{E_m} - \beta_m E_m^2\right)E_m W\right] + D_E\frac{\partial^2 W}{\partial E_m^2} \tag{12}$$

and its phase Φ:

$$\frac{\partial \Phi}{\partial t} = q\frac{\partial^2 \Phi}{\partial \varphi^2}, \tag{13}$$

where $q = D_\varphi/E^2$ and D_E and D_φ are the strengths of the amplitude and phase noise.

The stationary solution of Eq. (12) has the form

$$W(E) = C\exp\left[\frac{1}{D_E}\left(\alpha_m\frac{E^2}{2} - \beta_m\frac{E^4}{4}\right)\right], \tag{14}$$

from which it follows that when $\alpha_m < 0$ the value of the probability distribution for the field amplitude is a maximum and $\langle E\rangle = 0$, i.e., up to the threshold of generation the coherent average value of the field amplitude is equal to zero. In such a case the behavior of the emission by the active molecules is mainly determined by fluctuations and the radiation turns out to be uncorrelated, with Gaussian statistics. However, for $\alpha_m > 0$ the structure of the solution undergoes a serious change. A solution is now possible for which the probability distribution reaches its maximum value when $\langle E_m\rangle = (\alpha_m/\beta_m)^{1/2}$ which indicates the appearance of a regular coherent component of the maser radiation. The statistics of the maser radiation are then different from Gaussian.

Equation (13) for the phase distribution function is a diffusion equation with a diffusion constant inversely proportional to the radiation strength ($\propto E^{-2}$). The solution of this equation is well known:[18]

$$\Phi(t) = (4\pi q t)^{-1/2}\exp[-(\varphi - \varphi_0)^2/4qt]. \tag{15}$$

For the complete solution of the problem one must calculate not only the distribution function of the maser field, but also its correlation function and spectrum. In the general case one needs nonstationary solutions of Eqs. (12) and (13) for the calculation of the correlation function and the spectrum. Since there are for the general case no analytical expressions which are solutions of the Fokker–Planck equation we must for the calculation of the correlation functions have recourse to either approximate (for instance, variational) methods or to computer calculations. However, if we restrict ourselves merely to a consideration of phase fluctuations, the calculation of the correlation function

$$\langle E(t)E^*(0)\rangle \propto e^{i\Delta\varphi} \tag{16}$$

with the distribution function (15) leads to the expression[17]

$$\langle E(t)E^*(0)\rangle \propto \frac{1}{(4\pi q t)^{1/2}}\int_{-\infty}^{\infty}\exp\left\{\frac{-[\varphi(t)-\varphi_0(0)]^2}{4qt}\right\} \times \exp\{i[\varphi(t)-\varphi_0(0)]\}d\Delta\varphi = e^{-qt}. \tag{17}$$

Through measuring the correlation function (17) one can obtain information about the width $\Delta\omega$ of the spectrum.[3] For instance, the spectrum obtained from (17) by a Fourier transformation gives a contour with a line width $\Delta\omega = D_\varphi/E^2$.

If we now change from the magnitude of the total strength of the electromagnetic radiation to its value I_0 at the center of the spectrum (the observed intensity dependence of the width of the spectrum is normalized by the intensity at the center of the line profile) we find that

$$\Delta\omega = \left(\frac{c}{4\pi}\frac{D_\varphi}{I_0}\right)^{1/2}. \tag{18}$$

Such a behavior of the width of the spectrum has been observed for some strong H_2O maser sources[4–9] and corresponds to the Schawlow–Townes formula, well known in the theory of quantum generators, and it also agrees in the form of its intensity dependence with the expression found earlier for the spectra of stellar lasers.[3]

A large number of spatial harmonics with frequencies $\omega_m = mc/R$ can be coherently excited simultaneously in a cosmic maser in the case where the generation condition (8) can be satisfied for a number of modes. In that case the distribution of the power between the modes is determined by complicated nonlinear processes. Both competition (suppression) of the modes and coexistence of different modes are then possible. In the latter case multiple-mode[3] and nonstationary radiation with complex statistical and spectral properties can then occur.

6. CONCLUSION

In the framework of the approach considered above we find that a nonequilibrium bounded cosmic medium may change to a generation regime in which a number of problems which arise in the interpretation of the radiation from strong burst H_2O masers in the travelling wave amplifier model may find their most natural explanation. The level of nonequilibrium effects in strong burst H_2O masers can by all accounts be expressed so strongly that properties which are specific for the astrophysical medium start to manifest themselves: cooperative, coherent effects in the radiation. In that case the model of a cosmic maser as a standing wave amplifier is inapplicable for the explanation of the observed phenomena since it is based upon the assumption of the absence of phase and frequency correlations. As a result it is unable to explain such important effects as the strong dependence of the width of the spectrum on the magnitude of the intensity, the high degree of directionality of the maser radiation (spatial discrimination of modes), and also the nonstationarity of the regime of the cosmic maser radiation, and so on. All this requires that one takes into account new effects such as the possibility of the occurrence of a generator regime for the radiation in natural cosmic masers.

It is possible that the existing mechanisms[1-3] and the one proposed here for the occurrence of a generator regime in the nonequilibrium cosmic medium and the recently observed strong burst H_2O masers[4-8] may be one of the first examples of the manifestation of cooperative coherent processes under astrophysical conditions.

[1)] This is possible, of course, provided the coherence of the signal is not lost due to scattering by the inhomogeneities of the interstellar medium during the propagation from the source to the observer.

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