Hanlé monastery in Kashmir. However, this name has since been discredited (*8*). Other reported occurrences of possible $Mg_3Cr_2Si_3O_{12}$-bearing garnets are in kimberlites from Lesotho, Basutoland (*9*) and the České Středohoří Mountains, Czechoslovakia (*10*), and in xenoliths from kimberlite pipes (South Africa) (*11*). In these three instances, the garnets are from olivine-bearing ultramafic rocks, and the $Mg_3Cr_2Si_3O_{12}$ end member constitutes less than 9 percent of the total garnet composition. Bagrowski (*12*) reported finding a red chrome-rich pyrope in the Stockdale kimberlite pipe (Kansas). This analysis has since been discredited in that the $Cr_2O_3$ content was too high and it did not have the correct cation ratios (*13*). However, Brookins (*13*) does note the existence of a green garnet, which may be chrome-rich, in the Stockdale pipe.

Nixon and coauthors (*9*) and Fiala (*10*) have independently plotted refractive index against the $Cr_2O_3$ content for chrome-rich pyrope garnets. Both studies show a linear relation between the two variables, but the curves differ in slope. Further work is necessary to define more closely the physical properties of chrome-rich pyrope garnets.

The stability field for $Mg_3Cr_2Si_3O_{12}$ garnet is unknown, although Coes (*14*) has reported synthesizing it at high pressures and temperatures. The chrome-bearing uvarovite garnet ($Ca_3Cr_2Si_3O_{12}$) has been synthesized at 1 atm (*15*). It may be that $Mg_3Cr_2Si_3O_{12}$ garnet is unstable at low pressures and alters to more stable phases when the pressure is decreased. For example, by analogy with the aluminum-bearing reaction studied by MacGregor (*16*), the reaction

$$\underset{\text{forsterite}}{Mg_2SiO_4} + \underset{\text{garnet}}{Mg_3Cr_2Si_3O_{12}} \rightleftarrows \underset{\substack{\text{magnesiochromite}\\ \text{(chrome spinel)}}}{MgCr_2O_4} + \underset{\text{enstatite}}{4MgSiO_3}$$

is possible, and it is interesting that all the minerals of this reaction occur as inclusions in diamond, although not necessarily in the same crystal (*17*).

The differences in chemical composition between the garnet inclusions from diamond and the garnet (usually pyrope almandines) from the ultrabasic nodules in kimberlite are curious and as yet unexplained (*18*). With regard to the chemistry of the mantle, it should be noted that, besides chrome pyrope and chrome spinel, chrome diopside (*19*) also is an inclusion in diamond. These facts suggest that chromium plays an important role in the phase chemistry of the mantle and must be considered when proposing petrologic models for the mantle.

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**References and Notes**

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24 May 1968

## Galactic X-rays: Variable Sources in Hydromagnetic Waves

Abstract. *Galactic sources of x-rays fluctuating in intensity are explained as being small regions, of enhanced gas density and temperature, emitting thermal Coulomb bremsstrahlung of kiloelectron-volt energies. Hydromagnetic wave motions, of the magnetic fields in the galactic spiral arms, produce the enhanced regions by compressing the clouds of ionized gas to which they are tied by their high electrical conductivity. From the observed periods of fluctuation of a few months, together with the hydromagnetic velocity, it is estimated that the average size of sources does not exceed $10^{16}$ centimeters. By using the formula for Coulomb bremsstrahlung and requiring that the sources shall produce the observed x-ray fluxes, one finds a second estimate of size of sources in agreement at about $10^{16}$ centimeters. Such regions are too small to be observable radio sources with current radio telescopes.*

Good evidence is accumulating from balloon and rocket experiments that Cygnus X-1 is an x-ray source of variable intensity; for x-rays of from 1 to 100 kev its intensity varies by factors of from 2 to 6 within periods as brief as 18 months, and both decreases (*1*) and increases (*2*). Similar but less well-substantiated fluctuations of the Crab nebula are deduced (*3*), at energies above 20 kev, from balloon experiments; the fluctuations may be by factors of from 2 to 5 within as little as 1 month. Likewise Centaurus XR-2 is reported (*3*) to have decreased and perhaps to have increased its intensity. Some 20 galactic sources (*4*) of x-rays have been reported since the first discovery in 1963. Because so many have been discovered by a few rocket and balloon experiments searching a small fraction of the sky, many more sources probably will be found.

We now propose an explanation of these variable sources, of the near-equality of their x-ray intensity (the known sources have intensities comparable within a factor of about 20), of their small sizes, and of their ability to both increase and decrease in intensity within brief periods. We predict that they will be found in abundance in the galactic arms.

We propose that the plasma producing the x-rays is the ionized gas of the galactic arms themselves, with average particle density of about 1/cm$^3$ and average magnetic field about $6 \times 10^{-6}$ gauss at about 300°K (*5*), but with a distribution of lower and higher densities and magnetic fields, in regions of various dimensions.

Such enhancements probably are caused by sinusoidal motions of the magnetic lines of force, accompanied by compression and rarefaction of the gas masses in the spiral arms, these having a sufficiently high electrical conductivity to be attached to the magnetic lines of force (*5*). Oscillations of hydromagnetic waves traveling in the gas clouds create regions having fluctuating increases and decreases in gas pressure, in magnetic fields, and in their own dimensions. Thus we expect the galactic arms to have a lumpy construction, with a distribution of larger and smaller regions of higher and lower gas densities and magnetic fields.

In regions of sufficient compression, the gas becomes hot enough to emit x-rays. The fluctuations of gas pressure, being adiabatic, cause temperature changes according to

$$T_2 = T_1(V_1/V_2)^{\gamma-1} = T_1(V_1/V_2) \quad (1)$$

where $\gamma=2$ for ionized H and He gas in a magnetic field. For x-rays of about 5 to 100 kev, a gas temperature of about $6 \times 10^7$°K suffices, corresponding to an adiabatic volume decrease in the ratio $V_1 : V_2$ of about $2 \times 10^5$.

Fluctuations in magnetic-field strength travel with the velocity of the transverse magnetohydrodynamic wave:

$$v = H/(4\pi\rho)^{1/2} \quad (2)$$

In the local spiral arm (5), with $\rho = 2 \times 10^{-24}$ g/cm³ and $H = 6 \times 10^{-6}$ gauss, this velocity averages about $2 \times 10^6$ cm/sec.

In regions of enhanced density, pressure, and magnetic fields, the velocity increases. Let the transverse perturbation of the wave be $y_1$ and let it decrease to $y_2 = y_1/\alpha$; then the magnetic field $H_1$ increases to $H_2 = \alpha^2 H_1$, the volume $V_1$ decreases to $V_2 = V_{1/\alpha^2}$, the density $\rho_1$ increases to $\rho_2 = \alpha^2\rho_1$, and the temperature $T_1$ increases to $T_2 = \alpha^2 T_1$. The velocity becomes $v_2 = \alpha v_1$. Thus enhanced regions emitting x-rays, and developing increased x-ray intensity within times of the order of a few months, have a wavelength

$$\lambda \leqq v_2(3 \times 10^6 \text{ seconds}) = \alpha 4 \times 10^{13} \text{ cm}$$

For regions at $6 \times 10^7$°K, emitting kiloelectron-volt x-rays and having $v_1 \sim 1.3 \times 10^6$ cm/sec, we find

$$\alpha = 450$$
$$v_2 \cong 6 \times 10^8 \text{ cm/sec}$$
$$\lambda \sim 1.8 \times 10^{15} \text{ cm}$$

An emitting region may consist of a wave train of several wavelengths, and thus a dimension $R$ is about $10^{16}$ cm. Here we have estimated the size of the fluctuating x-ray sources from the time of scintillation and local hydromagnetic velocity.

The gas in these hot, compressed regions of increased density (particles, about $2 \times 10^5$/cm³) emits x-ray kiloelectron-volt energies at the intensities observed for galactic x-ray sources. To demonstrate this assertion we use well-known formulas (6) for Coulomb bremsstrahlung emission. The total isotropic power of a Maxwellian plasma at temperature $T$(°K) is

$$p = 1.44 \times 10^{-27}(T)^{1/2} N_i n_e Z^2 \text{ erg/cm}^3 \cdot \text{sec} \quad (3)$$

We note that the total power scales as $\alpha^5$. Let $V$ be the volume of the x-ray source at distance $d$ from Earth. The power received on Earth is about $10^{-8}$ erg/cm² • sec. Thus we require

$$1.44 \times 10^{-27}(T)^{1/2} N_i n_e V = 10^{-8}\, 4\pi d^2 \quad (4)$$

Letting $d \sim 1$ kpc (kiloparsec) and $T_2 = \alpha^2(300°\text{K})$, with ion and electron densities $(N)_2 = \alpha^2(N)_1$ where $N_1$ is the average density, we require

$$\alpha^5 N_1 n_1 V = 4 \times 10^{61} \text{ erg/sec} \quad (5)$$

When one makes $N_1 = n_1 = 1$/cm³ and $\alpha = 450$, it follows that

$$V = 4\pi R^3/3 = 2.2 \times 10^{48} \text{ cm}^3$$
$$R \cong 0.8 \times 10^{16} \text{ cm} \quad (6)$$

This estimate of the average dimension of the compressed hot regions agrees with our earlier estimate based on the time in which the x-ray intensity changes and on the enhanced hydromagnetic velocity. Regions of such compression and dimension are not radio sources observable with current radio telescopes (7). The time for cooling by emission of bremsstrahlung is about 1000 years. The probability that the plasma, at the 10-kev temperature achieved by compression, will suffer infrared degeneration is negligible because photons do not collide in so small a region.

The number of these sources may be estimated, by use of Kolmogoroff's theorem relating the total turbulent energy of wave number $k$ to the $5/3$ power of the wavelength, as follows: let there be $n_1$ regions of wavelength $L_1 \sim 10^{16}$ cm and enhanced energy $2 \times 10^5\ E_0$, where $E_0$ is the mean energy density of turbulence in the galaxy. Let the total volume of average regions, wavelength $L_0 \sim 3$ kpc $= 10^{22}$ cm, be $V_0 \sim 10^{67}$ cm³. Then the total energy of average regions is $E_0 V_0$ and that of the hot regions is $2 \times 10^5\ E_0 V_1$. Kolmogoroff's relation provides that (8)

$$E_0V_0/(2 \times 10^5)E_0V_1 = E_0V_0/(2 \times 10^5)E_0L_1^3 n_1 = (10^{22}/10^{16})^{5/3}$$
$$n_1 L_1^3 \cong 5 \times 10^{51}$$
$$n_1 \sim 5000$$

(Note that in estimating that $L_0 \sim 10^{22}$ cm we have made allowances for the fact that the average wavelength along the arms can be longer than across them. We take for the galaxy a diameter of 30,000 parsecs and a thickness of 50 parsecs.)

Thus about 5000 regions of about $10^{16}$-cm diameter could be x-ray sources fluctuating with a period of a few months. Many of these sources no doubt would be obscured by galactic dust.

A diffuse (unresolved) x-ray background has been observed coming from the galaxy; it may be explained as coming from many hot (9) regions smaller than $10^{16}$ cm, closely spaced, and probably partially overlapping each other. Because many thousands of fluctuating sources are averaged in this background, it is not expected to change with time.

The frequency dependence of the Coulomb bremmstrahlung fits within experimental error to the observed spectral distributions of x-ray sources if a correction for interstellar attenuation is made at the longer wavelengths (below 5 kev) (10).

Binary stars (11), globular clusters in the arms, explosions of novae and supernovae, solar systems, and high-velocity stars moving on trajectories that crisscross the galactic plane are effective sources of sinusoidal disturbances in the magnetic plasma of the galactic arms, in addition to the motion described by Chandrasekhar and Fermi (5). Therefore we may expect fluctuating x-ray sources to abound in their neighborhoods and in the hydromagnetic waves propagating from them, and to appear and disappear as the disturbances compress and rarefy.

It is unlikely that variable x-ray sources will be observed in other galaxies because of the great distances involved. The recent failure to observe x-rays from the Magellanic Clouds (12) (distance, about 50 kpc) agrees with this prediction.

Magnetic compression has been demonstrated in the laboratory. The theta-pinch and the high-density-focus experiments of Los Alamos and other controlled-fusion laboratories have obtained plasma compressions of a factor of 50, produced with magnetic fields. With larger banks of condensers one expects to increase this factor (13).

The minimum size of observable regions can be smaller than $10^{16}$ cm when hydromagnetic disturbances pass through galactic clouds of higher density. Most interstellar galactic matter appears to be concentrated into cloud-like complexes (14) having dimensions of about $10^{18}$ to $10^{20}$ cm and densities of about 10 atoms per cubic centimeter but varying greatly in size. And even denser structures exist, usually of smaller dimensions. Obviously such kernels provide excellent starting conditions for production of observable sources of x-ray emission, with magnetic compressions.

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$$\overline{p} = [66 \times 10^{-10}\ (\text{gauss})^2(\text{Gev})^2]\ \text{erg/sec per electron}$$
$$\nu_o = [6 \times 10^{12}\ (\text{gauss})\ \text{Gev}^2]\ \text{sec}^{-1}$$

For a source cell having volume $V$, density of 10-kev electrons $= \alpha^2 N_1$, and magnetic fluid $\alpha^2 N_1$, distant from Earth by $d$, the intensity received on Earth would be

$$\frac{V(\alpha^2 N_1)}{4\pi d^2}\ \frac{\overline{p}}{\nu_o} \cong 10^{-30}\ \frac{\text{watt}}{\text{m}^2 \bullet (\text{cy/sec})}$$

Thus both Coulomb and magnetic bremsstrahlung intensities are far below threshold sensitivity for radio telescopes. A second mechanism of x-ray emission in these regions —namely synchrotron emission by the electron component of primary cosmic rays traversing the enhanced magnetic fields—is likewise of small intensity.
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$$p(\nu) \cong (kT_2)^{-1/2}\,(Ne\quad Ni)\exp(-h\nu/kT_2) \sim \alpha^3 \exp(-h\nu/kT_2) \sim \alpha^3 \text{ for } h\nu < kT$$

Thus power production in any given frequency mode $\nu$ varies as the cube of compression ($\sim \alpha^3$), for frequencies below the temperature $h\nu < kT$.
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## Flocculation Mechanism: Charge Neutralization and Bridging

**Abstract.** *Electrophoresis measurements and electron-microscope observations with two model colloids and a polymeric flocculant show zeta-potential changes and details of floc structure. Fibers of the flocculant extend radially from the particle surface and vary in thickness from 20 to 300 angstroms. Both charge neutralization and bridging may function simultaneously.*

The mechanism of flocculation is under study principally because of the current importance of removing colloidal contaminants from water. Such contaminants may be responsible for turbidity, they may carry odor and taste components on their surfaces, they may be difficult to remove, and most importantly they interfere with many tertiary or advanced waste-water treatments such as adsorption, filtration, and various membrane techniques. The relative importance of charge neutralization and bridging by polymeric flocculants is a highly controversial subject (*1*). Evidence for both mechanisms has now been obtained by electrophoresis measurements and electron-microscope observations on two widely different materials, a finely divided silica and a polystyrene latex.

Minusil No. 5 silica from the Pennsylvania Glass Sand Corporation has a particle diameter of about 1 $\mu$ and a $\zeta$ potential of $-27 \pm 2$ mv, and has been used as a standard in electrophoresis studies in this and other laboratories. Dow LS-052 Å polystyrene latex has a particle size of 1260 Å and a $\zeta$ of $-50$ mv, and has been used as a standard in electron-microscope studies. The cationic polymeric flocculant, a polyamine sulfate (C-7) of high molecular weight, was obtained from Rohm & Haas. Water was twice distilled in quartz.

Electrophoretic mobilities were determined directly with a Zeta Meter which measures particle velocities in both directions by reversing polarity (*2*). The $\zeta$ potential was calculated from particle velocity by means of the Helmholtz-Smoluchowski equation, $\zeta = 4\pi u\eta/D$, in which $u$ is the electrophoretic mobility, and $\eta$ and $D$ are, respectively, the viscosity and the dielectric constants of the liquid in the boundary layer.

Samples were prepared for the electron microscope by direct deposition of the colloidal solutions onto collodion supports. Some were shadowcast (*3*) to improve visibility. This is often necessary, because even relatively thick structures of organic polymers and certainly their thin fibers are transparent to the electron beam. Moreover, shadowcasting provides the third dimension.

Calculation of "equivalent monolayers" of adsorbed flocculant involves several assumptions and simply provides a tentative basis for mechanism considerations. An approximate surface area of the colloidal silica is based on particle-size measurements on the electron microscope as well as on observations made in the Zeta Meter. The indicated particle size of about 1 $\mu$ is equivalent to a surface area of approximately 1 m$^2$/g. The surface area of the horizontally oriented polymer is assumed to be about 1000 m$^2$/g, based on considerable thin-film work with polar polymers (*3*). Minimum coiling or folding of adsorbed polymer and an approach to complete adsorption are assumed.

Concentrations, calculated "equivalent monolayers" [(parts per million of flocculant × 1000)/(parts per million of colloid)], electrophoretic mobilities, and $\zeta$ values for colloidal silica with the C-7 flocculant are listed in Table 1. The $\zeta$ of the original particles,

Table 1. Zeta potential of colloidal silica on the addition of a cationic polymeric flocculant.* Abbreviation: ppm, parts per million.

| Cationic polymeric flocculant | | Electrophoretic mobility ($\mu$/sec per volt/cm) | Zeta potential (mv) |
|---|---|---|---|
| ppm | ("Monolayers") | | |
| 0 | 0 | 2.1 | −27 |
| 0.01 | 0.1 | 2.2 | −28 |
| 0.05 | 0.5 | 0.88 | −11 |
| 0.075 | 0.75 | (0) | (0) † |
| 0.10 | 1.0 | 0.66 | + 9 |
| 1.0 | 10 | 2.0 | +26 |
| 10 | 100 | 2.1 | +27 |
| 50 | 500 | 2.0 | +26 |
| 100 | 1000 | 2.0 | +26 |

* 100 ppm Minusil No. 5 colloidal silica with the C-7 flocculant. † Athough most particles are motionless ($\zeta$ = zero), some show a small negative $\zeta$.