

A Plasma Hypothesis for Anomalous OH Emission

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Although the maser hypothesis for anomalous OH emission encounters difficulties it has not been seriously questioned because, as pointed out by Turner,¹ no alternative has been available. The following ideas might suggest that there is an alternative hypothesis for anomalous OH emission.

Outline of a Possible Alternative Hypothesis

It has been proposed^{2,3,4} that OH emission sources are situated in the atmospheres or surroundings of protostars. For a reasonable range of parameters free electrons and molecules can coexist in the atmosphere of a protostar. Suppose that in a particular region the plasma frequency were equal to the frequency of some molecular transition, then if plasma waves were excited resonant scattering by the molecules could lead to non-thermal line emission. This suggestion (by J. P. Wild, private communication) would appear to be an alternative to the maser hypothesis; it will be called the plasma hypothesis for anomalous OH emission.

An immediate objection which might be raised is that the observed angular sizes of individual OH sources imply sizes of a few astronomical units; this would be unacceptably large for a partially ionized region with $n_e \sim 3 \times 10^{10} \text{ cm}^{-3}$, as required here. However, the observed angular sizes may be due to scattering in the source region or in the interstellar medium (see the discussion by Little⁵ and references cited therein). Electron densities of the order required could be attributed to a chromosphere-type region.

A number of attractive features of the plasma hypothesis are outlined below. One feature is that the non-thermal character of the radiation is due to the plasma waves - these can be excited by shock waves, as in type II solar radio bursts: the OH molecules, which must have a normal rather than an inverted energy population, merely scatter the (highly non-thermal) electron plasma waves into (highly non-thermal) transverse waves which escape. Unfortunately, in the formulation of a specific model based on the plasma hypothesis, an impossible requirement is encountered. Perhaps this could be overcome in a different kind of model, but otherwise it would appear to make the hypothesis untenable. A resonance between the plasma frequency and a molecular transition frequency may well have other astrophysical applications.

Resonant Scattering of Plasma Waves

The maser hypothesis was invoked to explain the following anomalous properties of OH emission sources.

- (a) High brightness temperatures (up to 10^{13} K) at the natural frequencies 1612, 1665, 1667 and 1720 MHz.
- (b) Very narrow bandwidths.
- (c) Line ratios markedly different from the thermal ratios 1:5:9:1.⁶

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(d) Peculiar polarization, often nearly circular.⁷ The maser hypothesis can account for properties (a) and (b); it offers no ready explanation of the actual line ratios and polarizations observed (properties (c) and (d)); the usual argument is that the anomalous line ratios and the observed polarization could be attributed to saturation of the maser but no quantitative theory of such saturation effects exists. Perhaps the major difficulty with the maser hypothesis is the identification of an adequate pumping mechanism.

The plasma hypothesis described here involves three ideas: (i) resonant scattering, usually called resonance fluorescence,^{8,9} can simulate line emission; (ii) emission close to the plasma frequency leads to a narrow bandwidth because the refractive index is much less than unity; and (iii) scattering of electron plasma waves into transverse waves is known to lead to non-thermal radiation in solar radio bursts of types II and III (where the electron plasma waves are generated respectively by a shock wave and a stream of electrons).

Plasma Parameters

By hypothesis the plasma frequency must be equal to one of the natural frequencies of OH emission. This fixes the number density of electrons at one of four values in the range

$$n_e = (3.2 \text{ to } 3.6) \times 10^{10} \text{ cm}^{-3}. \quad (1)$$

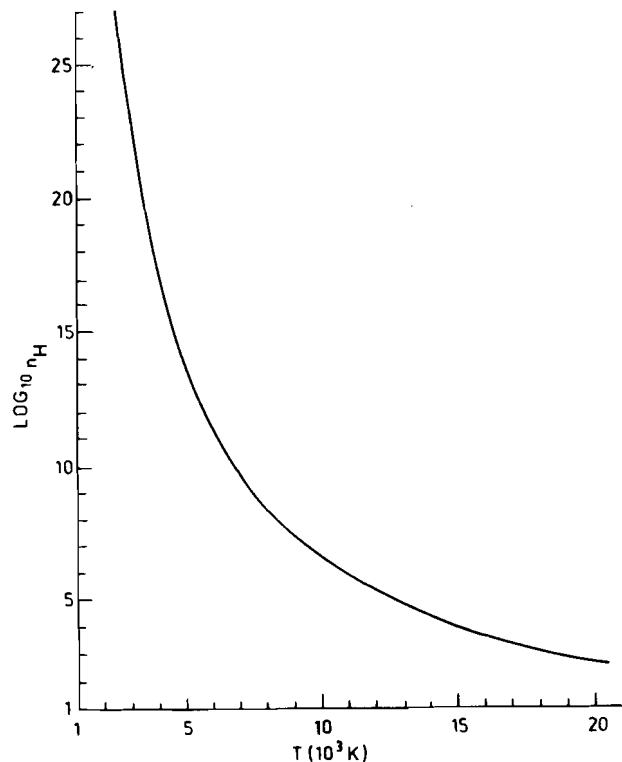


Figure 1. The solution of Saha's equation $\log n_H = 2 \log n_e = 13.60 + 1.5 \log \Theta - 20.94$ with $\Theta = 5040/T$ is plotted as a function of T in units of 10^3 K .

Both this relatively high density and the requirement that the plasma waves be maintained at a highly non-thermal level (e.g. by shock waves) could be explained by locating the source of OH emission in the atmosphere of a protostar.

The remaining plasma parameters can be estimated by assuming normal cosmic abundances and thermal equilibrium. Then the only free parameter is the temperature. Over a wide range of values of the number density n_{H} of neutral hydrogen, n_{H} should be given by the solution of Saha's equation with specified n_{e} (see Figure 1). Acceptable temperatures would be $4 \times 10^3 \text{ K} < T < 13 \times 10^3 \text{ K}$.

For temperatures in this range order-of-magnitude estimates of the molecular abundances give

$$n_{\text{H}} \gg n_{\text{H}_2} \sim n_{\text{O}} \gg n_{\text{OH}} \gg n_{\text{H}_2\text{O}} \sim n_{\text{O}_2}, \quad (2)$$

with negligible abundances of negative ions, e.g. $n_{\text{H}^-} \ll n_{\text{H}}$, $n_{\text{O}^-} \ll n_{\text{O}}$. Under these conditions OH is formed by the process $\text{H} + \text{O} \rightarrow \text{OH}$ and is destroyed by $\text{H} + \text{OH} \rightarrow \text{H}_2 + \text{O}$.¹⁰ Solomon's¹⁰ estimate with a correction of a factor of 80 (see note 13 of Ref. 11) is

$$n_{\text{OH}}/n_{\text{H}} = 4 \times 10^{-9}, \quad (3)$$

$$\dot{n}_{\text{OH}}/n_{\text{OH}} = 10^{-11} n_{\text{H}} \text{ s}^{-1}, \quad (4)$$

where $\dot{n}_{\text{OH}}/n_{\text{OH}}$ is the destruction rate (= creation rate) of OH. The inverse of (4) is the lifetime of an OH molecule.

Resonant Scattering

A simple classical model for the resonant scattering cross-section σ_{R} at a line with frequency f (in hertz), natural width Γ (in s^{-1}) and total width Γ_{t} (in s^{-1}) is that quoted by Jackson:¹¹

$$\sigma_{\text{R}} = \frac{3}{2\pi} \frac{c^2}{f^2} \left[\frac{\Gamma}{\Gamma_{\text{t}}} \right]^2 \quad (5)$$

For the two main (satellite) lines of OH one has¹³ $\Gamma \approx 7 \times 10^{-11} \text{ s}^{-1}$ ($\Gamma \approx 1 \times 10^{-11} \text{ s}^{-1}$). In the present case the total width Γ_{t} is determined by the lifetime of the OH molecules:

$$\Gamma_{\text{t}} = \dot{n}_{\text{OH}}/n_{\text{OH}}. \quad (6)$$

Bandwidth and Polarization

By analogy with type II solar radio bursts the mechanism is capable of accounting for brightness temperatures of the order observed. (If the actual area of the source is much less than the apparent area, owing to effects of scattering, the actual brightness temperature is correspondingly higher than the apparent brightness temperature; this needs to be taken into account here but it presents no intrinsic difficulty.)

The observed bandwidth Δf of approximately a few kilohertz is much greater than Γ_{t} . Doppler broadening due to thermal motion of OH molecules at 10^4 K ($\beta_{\text{th}} \approx 7 \times 10^{-6}$) gives a bandwidth

$$\Delta f = \mu \beta_{\text{th}} f \quad (7)$$

of the order observed, provided the refractive index $\mu = (1 - f_{\text{p}}^2/f^2)^{1/2}$ is in the range 0.1 to 0.3. Scattering of plasma waves with phase speed v_{ϕ} gives transverse waves with refractive index

$$\mu = \sqrt{3} V_{\text{e}}/v_{\phi}, \quad (8)$$

where V_{e} is the thermal speed of electrons. The inferred phase speeds $v_{\phi} \sim (5 \text{ to } 15)V_{\text{e}}$ are plausible.

Circular polarization arises in the presence of a weak magnetic field by the same mechanism as for type III bursts (see e.g. Kai¹⁴): 100 per cent circular polarization requires a magnetic field strength

$$B \gtrsim 10^3 (V_{\text{e}}/v_{\phi})^2 G, \quad (9)$$

e.g. $B \gtrsim 10 G$ for $v_{\phi} = 10 V_{\text{e}}$.

The Impossible Requirement

There is a background broadband emission arising from the scattering of the plasma waves by the thermal ions. For emission in a line with bandwidth Δf to be observable while the broadband background is unobservable, the power generated in the bandwidth Δf due to scattering by OH molecules must exceed the power generated in the same bandwidth due to scattering by the thermal ions. This leads to the requirement

$$\frac{\sigma_{\text{R}} n_{\text{OH}} \Gamma_{\text{t}}}{\sigma_{\text{T}} n_{\text{e}} \Delta f} > 1 \quad (10)$$

where σ_{T} is the Thomson cross-section.

On inserting the above parameters in (10) the only free parameter n_{H} drops out. The left-hand side of (10) gives 10^{-5} ($10^{-5} \div 50$) for the two main (satellite) lines. Thus (10) is an impossible requirement on the model.

The condition (10) is an impossible one when the abundances are determined as above, i.e. by assuming local thermodynamic equilibrium (LTE). The coexistence of free electrons and OH molecules under highly non-LTE conditions seems implausible (e.g. knowledge of the ionosphere makes it implausible that OH molecules would be abundant when ionization is by UV radiation).

It is noteworthy that the parameters $n_{\text{e}} \sim 3 \times 10^{10} \text{ cm}^{-3}$ and $T \sim 10^4 \text{ K}$ are close to those obtaining in the solar chromosphere. Emission of molecular lines in the microwave range by this mechanism from shock waves in the chromospheres of the Sun and similar stars remains a possibility which should be investigated.

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