

THE DETECTION OF QUARKS IN DIFFUSE NEBULAE

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ABSTRACT

The problem of detecting quarks in diffuse nebulae is studied, considering the existence of hydrogenic quark atoms. It is shown that the predicted upper limit of abundance, relative to hydrogen, is 1.5×10^{-8} if the infrared lines produced by the quark atom are used.

RESUMEN

El problema de la detección de quarks en nebulosas difusas es analizado, considerando la existencia de átomos quárquicos hidrogenoides. Se predice que el límite superior de abundancia es 1.5×10^{-8} , relativa al hidrógeno, cuando se usan las líneas infrarrojas producidas por el átomo quárquico. El límite es dos órdenes de magnitud más pequeño que el valor correspondiente para el espectro solar.

I. Introduction

After Gell-Mann (1964) and Zweig (1964) introduced the quark hypothesis in order to explain the multiplet structure of the hadron families, several attempts have been made to establish the physical existence of such fractionally charged particles. Searches were carried out in different places: high energy accelerators, high energy cosmic ray reactions and electrolysis of large amounts of sea water. So far, the results obtained in those experiments seem to be inconclusive. Astronomically the search has been undertaken in the solar spectrum; Sinanoglu *et al.* (1966) sought for evidences, in the ultraviolet region, for C, N and O atoms with quarks attached to their nuclei, obtaining negative results.

Due to the conservation law of the electric charge, a quark must decay only into a fractionally charged particle; when the ground state is reached, the resulting quark must be stable. Therefore, one could expect the existence of quark atoms; that is, a nucleus with an atomic mass number $1/3$ and charge $2/3 e$, with a bound electron. The corresponding Balmer and Lyman series of lines, produced by this atom, fall in the near infrared and in the rocket ultraviolet region. Leacock *et al.* (1968) have searched in the ultraviolet and infrared parts of the solar spectral tables for evidence of these theoretical series of lines. Their detailed analysis provided upper limits for the photospheric quark abundance; the upper limit is 10^{-6} per hydrogen atom, as derived from the infrared line spectrum. This value agrees perfectly with the limit of 8×10^{-7} , obtained by the usual methods of curve of growth analysis. The large number of spectral lines in the ultraviolet region difficulties the search, and a clear evidence of a Lyman series cannot be definitely established; then, the upper limits computed by Leacock *et al.* range from 10^{-7} to 10^{-9} . On the other hand, a curve of growth calculation cannot provide a more accurate number.

The possibility of seeking quarks in the diffuse nebulae is interesting for two main reasons; the low density of these objects could reduce the quark interaction with other particles; secondly, the nebular spectrum is, by far much, simpler than any stellar spectrum and, consequently, the line spectrum can be more easily identified. In the present work, the hydrogenic quark atom is assumed to be present in nebulae, and its radiative properties are computed. The results are used to predict the upper limits for quark abundances, which can be obtained with present observational techniques.

II. The radiative recombination coefficients

The computation of the effective recombination coefficients for hydrogenic atoms is a well-known process developed by several authors to a high degree of accuracy (Pengelly, 1964, Clarke, 1965). For simplicity, the method proposed by Seaton (1959) will be employed. The assumptions to be made are: the nebula is optically thick for the Lyman lines (except $L\alpha$), and the production of lines occurs only by radiative recombination.

As defined by Seaton, the effective recombination coefficient for the the n - m transition is given by:

$$\alpha_{nm}(T) = P_{nm} \sum_{l=n}^{\infty} \alpha_l C_{ln} \quad (1)$$

where the cascade matrix C_{ln} represents the probability that a capture on a level l is followed by a transition to level n , including the various modes of cascade. The elements of C_{nl} , tabulated by Seaton, apply to the quark atom, and thus do not need to be computed again. P_{nm} is defined by:

$$P_{nm} = \frac{A_{nm}}{\sum_{m=1}^{n-1} A_{nm}} \quad (2)$$

where the A_{nm} 's are the Einstein's spontaneous emission coefficients; and $\alpha_n(T)$ denotes the radiative recombination coefficient for level n , whose algebraic expression is, with the usual notation:

$$\alpha_n(T) = \frac{1}{c^2} \frac{2^{1/2}}{\pi} (mkT)^{-2/3} 2 n^2 e^{x_n/kT} \int_{x_n}^{\infty} (h\nu)^2 e^{-h\nu/kT} a_n(\nu) h d\nu \quad (3)$$

with the absorption coefficient $a_n(\nu)$ expressed in terms of the Gaunt factors $g_{II}(n, \epsilon)$ and the energy of the free electrons ϵ , according to:

$$a_n(\nu) = \frac{2^6}{3\sqrt{3}} \alpha \pi a_0^2 r (1 + n^2 \epsilon)^{-3} g_{II}(n_1, \epsilon) \quad (R)$$

in which the integral is readily evaluated by numerical methods, and where the recombination coefficients are derived from equation (1). Computations were carried out for two different values of the electron temperature, considering a 10^{-4} level atom. Some of the results are presented in table 1.

TABLE 1
Effective recombination coefficients

	T=20,000°K	T=10,000°K
α_{32}	3.0733	1.5820
α_{42}	0.6849	0.3948
α_{52}	0.3372	0.1626

Since the energy emitted by a given line is:

$$E = N_q N_e \alpha_{n2} h\nu_{n2} \quad (4)$$

we may calculate the relative intensities of the lines and predict the equivalent Balmer intensity decrement. Table 2 shows the results which could be directly compared with observational data.

TABLE 2
Balmer intensity decrement

$\lambda(\text{\AA})$	10 000°K	20 000°K
14766.49	331.2	296.7
10938.13	100.0	100.0
9766.19	55.1	46.0
9229.05	30.4	24.7
8932.81	18.3	12.8
8846.27	12.4	9.2
8788.65	1.2	0.5

III. On the upper limit of detection

The relative abundance of quarks can be directly determined from the observation of lines produced by the quark atoms. Since the intensity of a line is directly proportional to the density of quarks ions N_q , the relative abundance, with respect to hydrogen is:

$$\frac{N_q}{N_H} = \frac{F_{n2}^q}{F_{H\beta}} \frac{\lambda_{n2}}{\lambda_{H\beta}} \frac{\alpha_{42}(T_e)}{\alpha_{n2}^q(T_e)} \quad (5)$$

where the F 's represent the energy fluxes received at the earth, at the corresponding wavelength λ . In equation 5 the flux at $H\beta$ is taken as a reference. The upper limit for the abundance will be set by the minimum value of the flux F_{n2}^q , which can be measured with certain degree of accuracy.

If a photon counting device is used in the observations, as the detector, the number of events, recorded by the counting system, attached to a telescope of aperture D , will be:

$$N = \frac{\pi \lambda}{4 hc} D^2 \epsilon_\lambda t F_\lambda \quad (6)$$

where ϵ_λ is a factor that takes into account the quantum efficiency of the detector and the optical transmission of the observing system. T (in seconds) is the time during which the energy flux F_λ is being observed. For optical frequencies, the statistics that describes the photon fluctuations can be considered as Maxwellian. Therefore, the accuracy of a given measurement is:

$$\delta = \frac{\sqrt{N + (n_a + n_b) t}}{N} \quad (7)$$

the counting rate of the sky background noise is n_a , and n_b represents the counting rate corresponding to the instrumental noise. From equations (5), (6) and (7) one derives that:

$$\frac{N_q}{N_H} = \frac{\alpha_{42}(T_e)}{\alpha_{n2}^q(T_e)} \left[\frac{n_a + n_b}{t} \right]^{1/2} \frac{A}{F_{H\beta} \delta} \quad (8)$$

where A is a constant, depending on the aperture of the telescope and the characteristics of the detector.

As seen from earth the Orion Nebula is the brightest of all nebulae, providing the opportunity of detecting very faint lines. Considering the line $\lambda 9766.19$ of the Balmer series, produced by the quark atom, and assuming that the 200-inch telescope is used with such a counting device that ϵ_λ equals 0.02, with an accuracy of 20%, one has:

$$\frac{N_q}{N_H} = 1.5 \times 10^{-6} t^{-1/2} \quad (9)$$

the value of $F_{H\beta}$, is computed from the work by Méndez (1967), considering that a circular diaphragm of 140 seconds of arc is employed in order to observe the most dense region of the Orion Nebula.

Since the total number of photons in the Balmer lines is close to the number of $Ly^q\alpha$ quanta, one can obtain for the abundance ratio derived from the observation of the $\lambda 2734.46$, that:

$$\frac{N_q}{N_H} = 9 \times 10^{-8} t^{-1/2} \quad (10)$$

however, in this case, the earth's atmosphere will not permit the observation of this line.

As a conclusion, one can see that for reasonable observing times, of the order of 3 hours, the upper limit attained with the infrared lines will be of the order of 1.5×10^{-8} and of 9×10^{-10} with the $Ly^q\alpha$ line. These limits are lower than the corresponding numbers derived from the solar spectrum.

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