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ON PROBING COMETARY MAGNETIC FIELDS BY MEASURING DEPOLARIZATION OF RESONANCE FLUORESCENCE*

D. R. CROSLEY,† W. J. TANGO, AND R. N. ZARE‡
Joint Institute for Laboratory Astrophysics, Boulder, Colorado
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ABSTRACT

It is proposed that cometary fields may be measured through studies of the degree of polarization of molecular resonance fluorescence in comets. The size of the field it is possible to measure depends on the molecular emission system chosen. In particular, it would appear that studies of polarization in OH fluorescence could set an upper limit to the cometary magnetic field of the order of a few milligauss.

The magnitude of the magnetic field associated with a comet is a matter of some controversy. The presence of a cometary magnetic field can be deduced (Biermann and Lüst 1963) from (1) narrow filamentary tail streamers, (2) long-lived structures with sharp boundaries, (3) wavy structures and undulations in the comet rays, and (4) correlation of the acceleration of these structures with solar magnetic storms. An interplanetary magnetic field of solar origin with a magnitude of about 10^{-4} G lies in the plane of the ecliptic with magnetic lines twisted in the form of an Archimedes spiral (Fairfield and Ness 1967; Ness and Wilcox 1964, 1967). As a comet moves toward the Sun, the cometary plasma interacts with the solar wind to form a shock front, distorting and compressing the interplanetary magnetic-field lines in the region of the comet's head. This initial suggestion by Alfvén (1957) has since been treated in a quantitative manner (Biermann, Brosowski, and Schmidt 1967), indicating that it is the primary mechanism for the formation of type I tails. There has also been speculation on the existence of an intrinsic cometary magnetic field (Brandt 1962; Malaise 1963; Swings 1965).

As early as 1911, Schwarzschild and Kron suggested that the primary excitation mechanism in comets was resonance fluorescence excited by sunlight. Confirmation (Swings 1941; Hunnaerts 1959; Stawikowski and Swings 1960) of this fluorescence mechanism has been provided by the underpopulation of certain individual rotational levels observed in the molecular spectra corresponding to the positions of Fraunhofer lines in the solar continuum, and by the changes in excitation caused by the Doppler shift due to the comet's motion. Hyder (1966) has proposed the use of the polarization of the resonance radiation as a probe of the magnetic field associated with a comet, and from the sodium D-line data of the comet Ikeya-Seki (1965f) he deduced the directions of the field. However, Chamberlain (1967) pointed out that there were serious doubts concerning Hyder's conclusions and that no direct measurement of a cometary magnetic field in Ikeya-Seki does, in fact, exist. Hyder's idea for measuring a magnetic field by the depolarization of its resonance radiation is nevertheless valid; it is the purpose of this Letter to suggest that the proper choice of fluorescing species (in particular, molecules) would enable one to measure much weaker fields than the ~ 2 G lower limit set by sodium.

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† Present address: Department of Chemistry, University of Wisconsin, Madison, Wisconsin.

‡ Alfred P. Sloan Fellow.

The depolarization of resonance radiation by a magnetic field, the so-called Hanle effect, has received increasing attention as a means of measuring atomic lifetimes (Budick 1967) and has now been applied to the study of molecular excited states (Zare 1966; Crosley and Zare 1967*a*, *b*). In the absence of a magnetic field, the non-isotropic light excitation produces coherence in the degenerate excited-state magnetic sublevels. This coherence causes interference effects in the reradiated light, which give rise to certain angular-distribution patterns in the fluorescence. Application of a magnetic field with sufficient strength to split the magnetic sublevels by more than their natural line width (hence removing their degeneracy and destroying the coherence of the excited state) causes changes in these angular patterns. The quantum formulation of this phenomenon, as first worked out by Breit (1933) and subsequently rederived by Franken (1962), shows that the exact form of these spatial distributions depends on (1) the direction of the propagation and polarization vectors of the incident and emitted light relative to the magnetic field and (2) the angular-momentum coupling schemes in both the ground and excited states. For the general case, one finds that the intensity I of light in a given direction as a function of magnetic field H is given by the sum of a Lorentzian-type and a dispersion-type curve. For purposes of discussion we consider only the Lorentzian part,

$$I = C_1 + C_2[1 + (2g\beta_0\tau H/\hbar)^2]^{-1}, \tag{1}$$

appropriate to a right-angle geometry, where the direction of observation, the direction of excitation, and the direction of the magnetic field are mutually perpendicular. In equation (1) g is the Landé g-factor and τ the lifetime of the excited state, β_0 is the Bohr magneton, and $\hbar$ is Planck's constant divided by 2π. The ratio of polarized fluorescence to the total fluorescence for this right-angle geometry is given by $(C_1 + 2C_2)/2(C_1 + C_2)$ and depends on the structures of the upper and lower states as well as the specific transition(s). For most diatomic molecules this ratio ranges from 5 to 50 per cent and may be calculated from knowledge of the angular-momentum coupling schemes of the states involved. For other geometries (Breit 1933; Franken 1962) it is found that the behavior of I relative to H is always governed by the product of the two factors g and τ. More detailed considerations show that the direction and magnitude of the magnetic field in the plane perpendicular to the Sun-comet vector would be determined by depolarization studies. Comets which produce luminous tails are, by and large, young comets moving in orbits distributed at random with respect to the ecliptic plane; each one would, therefore, intersect the magnetic-field lines associated with the solar wind at a different angle. Additional information may thus be obtained by observations at different observer-comet-Sun angles and by studies of different regions of the comet.[1]

It is readily apparent from equation (1) that the order of magnitude of the field H necessary to produce a given amount of polarization depends on the parameters g and τ of the excited state. Clearly, to investigate very small magnetic fields, one must select a system whose upper state has a large g-value and a long radiative lifetime. For the case of the sodium D-lines, with $g = \frac{1}{2}$ and $\tau = 1.6 \times 10^{-8}$ sec, the amount of polarization in fields less than 2 G is virtually indistinguishable from that in zero field, thus rendering an effective lower limit to the usefulness of sodium as a probe of cometary magnetic fields.[2] On the other hand, molecules have a large number of emitting levels with varying g-values and lifetimes and offer a wide choice of useful ranges as probes of the cometary magnetic field.

[1] Due to the low densities assumed to exist in comets, effects of collisional depolarization may be neglected. Radiation-trapping effects will also be negligible.

[2] Error bars of the order of 20 per cent are assumed, somewhat better than Hyder obtained. Also, as Chamberlain (1967) points out, Paschen-Back effects in relatively low fields further complicate the analysis; for a quantitative treatment of this see Baylis (1967).

Several observers,[3] following Öhman's (1941) pioneering work in the field, have found polarized molecular resonance fluorescence in comets, in particular for the CN $B\,^2\Sigma^+ \rightarrow X\,^2\Sigma^+$ and $C_2\,A\,^3\Pi_g \rightarrow X\,^3\Pi_u$ band systems. Although much of this work was done at low dispersion, recent developments (Arpigny 1965) should allow polarization measurements to be made on individual rotational lines; this not only provides internal checks on the data but also increases the range of fields which can be measured since g is normally a function of the rotational level.

At present, nitric oxide is the only molecule whose depolarization characteristics have been studied in the laboratory (Crosley and Zare 1967*a*, *b*) which is likely to be present in comets. Although its cometary spectra have not yet been observed, this is presumably only because its emission bands are absorbed in the upper atmosphere, making earth-based observations impossible. It does offer the advantage of having a g-value independent of rotational level (Crosley and Zare 1967*b*), so that one could integrate the light over an entire vibrational band without need for subsequent statistical analysis. If a typical error of $\lesssim$15–20 per cent is assumed (see Öhman 1941), the lowest depolarization measurable with a signal-to-noise ratio of 1 corresponds to a field of 50–100 mG. This may be much larger than the fields actually present, but it would provide an upper limit substantially lower than that now available.

A much more promising candidate for depolarization studies would be the OH molecule, whose ultraviolet-band system ($A\,^2\Sigma^+ \rightarrow X\,^2\Pi$) has already been seen in comets. If we use the lifetime value (Bennett and Dalby 1964) $\tau = 10^{-6}$ sec and a g-value near 2 for the $K = 1$ state, a cometary magnetic field as low as $\sim$4 mG could be detected using this transition. Experimental investigations of OH are currently being carried out in this laboratory to establish its depolarization characteristics precisely.

Obviously, more experimental work needs to be done on the magnetic-field depolarization of resonance fluorescence in molecular spectra, in order to establish actual values of the field necessary for depolarization. Similarly, there exists a need for more polarization studies on cometary spectra—in particular, the observation of individual rotational lines. A combination of such laboratory measurements and astrophysical data will yield information on the nature of cometary magnetic fields.

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[3] See Wurm (1963) for a brief synopsis and references.

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