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Magnetic confinement of broad-line clouds in active galactic nuclei

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Summary. The region containing the clouds that emit the broad spectral lines in active galactic nuclei may be pervaded by a magnetic field of strength ~1 G. Magnetic stresses could then confine the clouds, obviating the need for a Compton-heated medium in pressure balance with the clouds.

1 Introduction

The broad emission lines in the spectra of quasars, radio galaxies and Type 1 Seyfert galaxies are attributed by many theorists to a population of clouds of density $\sim 10^{10}\,\mathrm{cm}^{-3}$, with estimated thickness $10^{12} r_{12}$ cm (where r_{12}=1–10) and internal sound speeds 10–20 $\mathrm{km\,s}^{-1}$ filling a small fraction of the central cubic parsec of these active galactic nuclei (AGNs). An individual cloud would expand and disperse in $\lesssim 10^6 r_{12}$ s – far less than the time it takes to cross the emitting region – unless it were confined by some external pressure. [See Ferland & Shields (1985) and Mathews & Capriotti (1985) for recent reviews, and Collin-Souffrin *et al.* (1987) for an alternative interpretation of the emission line region.]

A common assumption has been that the clouds are in pressure balance with a hot intercloud medium. A two-phase model, in which intercloud gas was heated by Compton scattering of the central continuum radiation, was developed in great detail by, in particular, Krolik, McKee & Tarter (1981). But problems with this model have subsequently been widely recognized (e.g. Ferland & Mathews 1987): the best data on the far-ultraviolet and X-ray continuum spectrum of AGNs imply a Compton equilibrium temperature no higher than 10^7 K; and unless some other process maintained the intercloud medium at least 10 times hotter, it could not supply enough pressure without being so dense that its opacity (due to photoelectric absorption as well as Thompson scattering) would be unacceptably large. Ferland & Mathews (1987) further argue that there would be problems with the dynamics and stability of the clouds if the internal sound speed in the intercloud medium were much less that the range in cloud velocities implied by the line widths (and less, also, than the likely virial velocity).

I wish to point out that the magnetic fields in the environment of the line-emitting clouds may well be ~1 G, and that magnetic stresses could then in themselves account for the confinement.

2 Magnetic fields in the central parsec

If there were a field between the clouds but not within them, then magnetic confinement would require a field strength such that

$$\frac{B^2}{8\pi} \gtrsim 3nkT \simeq 0.04\left(\frac{n}{10^{10}\,\mathrm{cm}^{-3}}\right)\left(\frac{T}{10^4\,\mathrm{K}}\right)\,\mathrm{erg\,cm}^{-3}. \tag{1}$$

A field of 1 G pervading the intercloud volume could therefore suffice to confine 'standard' broad-line clouds. The distance R of these clouds from the central continuum source scales roughly with $L^{1/2}$, being typically 10^{18} cm for quasars and 10^{17} cm for Seyfert 1 galaxies. Is the field around the clouds really likely to be as strong as this? One can make separate estimates based on three different assumptions about the primary power source.

(i) *Relativistic wind.* If a luminosity L_w, powered by electromagnetic extraction of a black hole's spin energy, emerged as a relativistic wind from near the hole, partly in kinetic energy and partly in Poynting flux, and a fraction f took the latter form, there would be a toroidal magnetic field of strength

$$B \simeq 0.4 f^{1/2}\left(\frac{L_w}{10^{46}\,\mathrm{erg\,s}^{-1}}\right)^{1/2}\left(\frac{R}{10^{18}\,\mathrm{cm}}\right)^{-1}\,\mathrm{G} \tag{2}$$

(the above assumes isotropic emission; there is a straightforward solid-angle correction if the outflow is beamed).

If the wind could not flow freely outwards, but was braked by encounters with external matter, the field could build up to equipartition even if it carried only a small fraction of the energy in the original wind. This is because the transverse flux depends on v_w^{-1}, so the magnetic energy density goes as v_w^{-2}. [There is an analogy here with the Crab Nebula, where a relativistic outflow, confined within a slowly-expanding envelope, is shocked at the location of the wisps; flux then accumulates in the body of the nebula, the magnetic stresses (proportional to the square of the accumulated flux) building up until they are strong enough to react back on the thermal and/or kinetic pressures (Rees & Gunn 1974).]

(ii) *Accretion flow.* In an AGN powered by accretion, the field could build up to equipartition with the kinetic energy density (i.e. $B^2/8\pi \simeq nkT_{\mathrm{viral}}$). This yields a value scaling, like expression (2), with $L^{1/2}$, but involving some further factors:

$$(V_{\mathrm{inflow}}/c)^{-1/2} \times (\mathrm{efficiency})^{-1/2}.$$

The expected field is therefore higher than expression (2), for a given luminosity.

(iii) *Accretion-driven wind.* A possibility in some sense intermediate between (i) and (ii) is an accretion flow where energy and angular momentum are carried away by a magnetised wind directed along the rotation axis (e.g. Blandford 1976 and Blandford & Payne 1982). If the outflowing material is loaded with sufficient plasma to make the outflow and Alfven speeds non-relativistic, this yields a magnetic field exceeding expression (2) by a factor $(v_w/c)^{-1}$.

Inserting $R = 10^{18}$ cm in any of the estimates above confirms that ~ 1 G is by no means an exorbitant strength for the field that might pervade the entire broad line region. Since the expressions for the field involve $L^{1/2}/R$, the argument works equally well for quasars and for Seyferts.

3 Interactions between field and cloud material

If the clouds were themselves unmagnetized (as would be expected if their constituent gas came from disrupted stars) they would be squeezed by the full pressure (equation 1) of the surrounding field. This is the 'melon seed' plasma configuration discussed by Schlüter (1956). In the astrophysical literature, this effect has been extensively discussed in the context of accreting neutron stars: see, for instance Arons & Lea (1980), Elsner & Lamb (1984), Michel (1977) and earlier references cited in these papers, or the review by Aly (1986). Cool accreted gas that penetrates within the stellar magnetosphere is compressed into diamagnetic blobs that can drop almost at the free-fall rate on to the star, 'pushing aside' the field. By analogy, in the AGN context the clouds need not share the kinematic properties of the intercloud magnetically-dominated plasma: small 'melon seed' clouds could be falling inwards 'upstream' with respect to an outflowing wind; loops of field might get trapped around larger clouds, however, as seems to be happening around some filaments in the Crab Nebula (Woltjer 1969; Swinbank & Pooley 1979).

An alternative possibility [especially in cases (ii) and (iii) above], is that the clouds and confining medium have identical provenance, but thermal instability has led to a two-phase medium. There would then be a field in the clouds, and the compression factor across the field direction would be limited by the associated field amplification. The kinematic coupling between the two components would then be closer: clouds tending to lag behind the flow would distort the tubes of force threading them, and would consequently be accelerated by the stretched field.

Even if there were no field in the clouds originally, it would gradually penetrate, and break up the clouds. This process would be uninterestingly slow if it were controlled by microphysical processes; it could be more rapidly achieved via Kelvin–Helmholtz instabilities, but even then penetration would be slower than the sound speed within the clouds.

The characteristic synchrotron cooling time at $R=10^{18}$ cm is shorter than the dynamical time-scales, so one might expect a low-beta plasma with most of the pressure in the field itself. There is a contrast here with the Crab Nebula, which has a volume comparable to that of the emission line region in quasars, but magnetic and radiative energy densities lower by 6–8 powers of 10. In the Crab, most of the pressure may be in a 'reservoir' of relativistic electrons; but in AGNs the particles radiate in less than the light travel time across the region.

Magnetically-confined clouds would acquire a streaky or filamentary structure, tending to elongate along the field. The field between the clouds would adjust towards a force-free configuration: it would be likely (in any of the three cases (i)–(iii) above) to have an overall axisymmetric structure. The line strengths would then depend on orientation in a similar manner to emission from a disc (appearing stronger when viewed along the symmetry axis), even if the clouds were isotropically distributed around the central continuum.

The interfaces between clouds and a magnetically-dominated intercloud medium are propitious sites for the acceleration of relativistic electrons, which would radiate *in situ*. The resultant continuum contribution enveloping the clouds, and therefore irradiating them from the outside as well as from the centre, would modify the expected line profiles for clouds of given kinematic properties.

Magnetic fields can therefore account for the confinement and survival of broad-line clouds, and eliminate the usual problems posed by the intercloud medium. The idea of magnetic confinement is already suggested for the clouds within the jets of some radio sources. These clouds lie as much as several kpc from the central AGN, and emit narrow lines (Whittle *et al.* 1986, 1987). The densities and field strengths in these narrow-line regions resemble those in the filaments of the Crab Nebula where magnetic confinement is also likely.

Note, finally, that the existence of still stronger fields at values of $R \ll 10^{18}$ cm is a natural consequence of the present hypothesis. It would therefore be natural to expect smaller and denser clouds confined by kilogauss fields close to the central continuum source. Such clouds would be too dense and hot to contribute optical-band emission lines, but would instead radiate roughly like black bodies with effective temperature such that $aT_{\mathrm{eff}}^4 = L/4\pi r^2 c$. If their covering factor were not too small, they could reprocess enough of the primary non-thermal continuum to contribute a substantial thermal bump in the ultraviolet (Guilbert & Rees 1987). There would be no sharp qualitative distinction, however, between the line-emitting clouds and the much smaller and denser cloudlets closer to the central object.

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