Physical constraints on the sizes of dense clouds in the central magnetospheres of Active Galactic Nuclei

Z. Kuncic*, E. G. Blackman and M. J. Rees
Institute of Astronomy, Madingley Rd, Cambridge CB3 0HA

ABSTRACT
The range of microphysical and global dynamical timescales in the central regions of Active Galactic Nuclei (AGN) is sufficiently wide to permit the existence of multiphase structure. In particular, very dense, cool clouds can coexist with a hot, magnetically-dominated medium and can thereby efficiently reprocess the continuum radiation generated in this primary source region. The strong dynamical forces in this central magnetosphere can give rise to extremely small clouds. Microphysical processes then determine whether such clouds can indeed survive, in spite of their extremely contrasting properties relative to the surrounding environment, for long enough to produce potentially observable thermal reprocessing signatures. We examine specific physical constraints on the thicknesses of such reprocessing clouds. Our results are plotted to show the range of conditions that is representative of the central regions of AGN. We find a parameter subspace in the extreme high density regime for which the effects of microphysical diffusion processes can be overcome and for which cool gas can maintain pressure equilibrium with the ambient magnetosphere.

Key words: galaxies: active – plasmas, magnetic fields

1 INTRODUCTION
The strong gravitational, radiation and magnetic fields in the central regions of AGN maintain any gas residing therein in a state of ongoing dynamical activity. The relevant microphysical timescales (e.g. thermalization, cooling) can, however, be extremely short compared to the global dynamical timescale (Rees 1984). This suggests that an instantaneous ‘snapshot’ could reveal the existence, albeit for a short time, of small structures close to thermal equilibrium that are capable of producing reprocessing signatures in the observed spectra.

Accreting gas exposed to the intense conditions in the central regions of AGN is unlikely to be homogeneous. It may consist of cool clumps of material embedded in much hotter and more tenuous gas (e.g. Pustil’nik & Shvartsman 1974; Stella & Rosner 1984). Such a multiphase picture has been successful in accounting for a variety of thermal reprocessing signatures in AGN spectra (e.g. broad UV emission and absorption lines, ‘warm absorber’ soft X-ray edges) which are inferred to arise from gas residing at distances (<1 pc from the central continuum-forming source (e.g. Davidson 1972; Weymann, Turnshek, & Christiansen 1983; Netzer 1993).

The presence of reprocessing material in the form of cool clumps residing in the central source itself is a particularly interesting possibility (e.g. Rees 1987; Ferland & Rees 1988; Celotti, Fabian, & Rees 1992; Barvainis 1993). The cool clouds are expected to be many orders of magnitude denser than the reprocessing gas residing further out and the strong confining forces can give rise to thicknesses which are extremely small by most astrophysical standards. Moreover, the clouds may be magnetically confined, since the primary continuum radiation is expected to be generated in a hot, dissipative environment that is structured and maintained by magnetic fields. Indeed, the presence of such thin clouds seems to be required in models for which the field strengths are at least in equipartition with the radiation field (e.g. Celotti, Ghisellini, & Fabian 1991). These unusual physical conditions warrant investigation: can such small-scale, dense clouds survive in the central magnetospheres of AGN long enough to be detected through thermal reprocessing signatures in the observed spectra?

A multiphase medium, with gas at different temperatures and densities coexisting at roughly the same pressure, can be maintained as long as the sound-crossing time across the thermal phases is shorter than the dynamical timescale. This condition for pressure support imposes an upper limit on the characteristic thickness of substructure in the form...
of localized dense regions cooling radiatively. The maximum height which can then be attained is just the pressure scaleheight, as determined by the confining forces of gravity, radiation and magnetic stresses. When the dynamical timescale is much longer than the radiative cooling timescale, gas can maintain thermal and radiative equilibrium and is thus capable of producing characteristic spectral signatures. In general, however, microphysical processes threaten the continued existence of spatially-distinct phases with contrasting physical properties and therefore impose a stringent constraint on the smallest thicknesses reprocessing clouds can maintain. Note that reprocessing clouds require only a very small fraction of the material in the central engine volume to be compressed, and this material need only be compressed in one dimension.

In this paper, we determine constraints on the thicknesses of radiative clouds which can survive against strong dynamical forces and large spatial gradients in a multiphase environment. In Section 2, we discuss the constraints on clouds imposed by their radiative and dynamical state. In Section 3, we examine mechanisms for cloud confinement and the implied pressure scaleheight. We then examine the microphysical diffusion constraints in Section 4. In Section 5, we present a plot of the cloud parameter space (density versus thickness) showing regions restricted by the above constraints for parameters that are representative of the innermost regions of AGN. We summarize and discuss our results in Section 6.

2 RADIAITON AND DYNAMICAL CONSTRAINTS

Consider a region of thickness $R$, located at a radial distance $r$ from the central mass in an AGN, in which the gas attains thermal equilibrium, with a corresponding electron temperature $T_e$. The gas attains an internal thermal and ionization balance when the timescale $t_{rad}$ for radiative cooling and recombination is much shorter than the characteristic dynamical timescale, which is of the order of the timescale $t_d$ for global free-fall when gravity dominates. For bremsstrahlung emission, very high electron densities are required to satisfy $t_{rad} \ll t_d$, with

$$n_e \gg 10^{16} \left( \frac{T_e}{T_{vir}} \right)^{1/2} \left( \frac{r}{r_h} \right)^{-2} M_7^{-1} \text{ cm}^{-3},$$

where $T_{vir} = m_p v_{A}^2 / k$ is the virial temperature corresponding to a free-fall speed $v_f = c (r/r_h)^{-1/2}$ and $r_h = GM/c^2 \approx (1.5 \times 10^{12}) M_7 \text{ cm}$ is the gravitational radius of a central mass $M = 10^7 M_7 M_\odot$.

Cool, dense clouds embedded in a hot, magnetically-dominated gas pervading the central continuum-forming region can only be sustained if the sound-crossing time $t_s$ for pressure equilibrium with the surrounding environment is shorter than $t_d$. This implies an upper bound on the characteristic thickness $R_{cld}$ of a cloud of gas,

$$R_{cld} < t_d v_s,$$

where $v_s$ is the internal sound-crossing speed at which the perturbations traverse the structure. Since gas in the central environments of AGN is most likely to be magnetized, the total internal sound speed is $v_s^2 = c_s^2 + v_A^2 = (2 k T_e / m_p) (1 + 1/\beta)$, where $c_s$ is the thermal sound speed, $v_A$ is the Alfvén speed and where $\beta = c_s^2 / v_A^2$ is the usual plasma beta parameter for the ratio of the thermal to magnetic pressure inside the gas.

Spatially-localized regions of dense, cool gas can be supported in an extended atmosphere by dynamical forces other than gravity; these generally set a more stringent limit to $R_{cld}$ than the sound-crossing-time constraint mentioned above. We next discuss some of the dynamical effects in AGN which can provide confinement mechanisms that enable discrete regions of cool, dense gas to coexist with an ambient hot, magnetically-dominated medium in a multiphase system.

3 CLOUD CONFINEMENT

Cloud survival relies on a confinement mechanism to prevent rapid expansion and dispersion at the internal sound speed. The speed in which the broad emission lines originate has been most successfully modeled as a two-phase environment, with cool clouds in photoionization equilibrium embedded in a hot, inter-cloud gas in Compton equilibrium (Krolik, McKee, & Tarter 1981). However, thermal pressure alone is insufficient to confine these clouds if the external medium is heated only by Compton scattering (Fabian et al. 1986). While additional heating mechanisms may be operating (Mathews & Ferland 1987), the strong radiation and magnetic fields which regulate the gas dynamics may provide the dominant contribution to the supporting pressure and confinement for clouds in radiative equilibrium (Rees 1986). Magnetic fields and radiation pressure also appear to provide a physically reasonable solution to the problems of confinement and acceleration of broad absorption line clouds in radio-quiet quasars (Beigelman, de Kool, & Sikora 1991).

Magnetic confinement is even more likely to be the case for reprocessing clouds in the central continuum-forming region, where magnetic fields are thought to provide the chief means of energy dissipation, so that the field strengths are at least in equipartition with the radiation field (e.g. Heyvaerts 1992).

3.1 The Pressure Scaleheight

The pressure scaleheight for thermal gas in the presence of strong gravitational, magnetic and radiation fields is deduced from the standard equation of magnetohydrostatic equilibrium,

$$n_e m_p g \left( 1 - \frac{g^*}{g} \right) = \nabla_i \left( n_e k T_e + \frac{B_i^2}{8 \pi} \right) + \nabla_j \left( \frac{B_i B_j}{4 \pi} \right),$$

where $g = GM/r^2$ is the gravity associated with the central mass and $g^*$ is an effective gravity describing the bulk acceleration due to internal radiation pressure resulting from photons as they traverse through and interact with the thermal gas. We discuss this effect in more detail below.

In the absence of dynamical forces other than gravity, the pressure scaleheight deduced from the equation of force balance is just

$$h = \frac{v_s^2}{g} = \frac{T_e}{T_{vir}} \left( 1 + \frac{1}{\beta} \right).$$
This corresponds to a self-consistent solution for a large-scale, optically-thin and magnetically-dominated atmosphere, with $v_A < v_r$. In the AGN context, such an atmosphere may form above the inner regions of an accretion disk owing to buoyant poloidal field lines, which provide an effective means of transferring stresses from the accretion flow (e.g. Leyvaerdt 1992).

In addition to hot, diffuse particles, clumps of denser and cooler material can also be present. Magnetic pressure can prevent such material from expanding laterally across the field lines. Consequently, the material elongates in alignment with the field, forming narrow filaments. In regions where the field lines are predominantly open, the filamentary clouds can be accelerated outward by surface forces in an accompanying wind or jet (e.g. Emmering, Blandford, & Shlosman 1992). In regions where the radial component of the field is small (i.e. tangled field lines or field loops), clouds can be locally confined by magnetic stresses due to a discontinuity in the tangent component of the field in much the same way as prominence structures are thought to survive in the solar corona (e.g. Kippenhahn & Schlüter 1957).

As we will discuss below, however, a physically different picture can arise when a strong radiation field is also present, as is the case for the central environment of AGN.

Clouds coupled to field lines can maintain a range of possible thermal pressures whilst maintaining total (thermal + magnetic) pressure continuity across the boundary,

$$n_{\text{cld}} k T_{\text{cld}} \left(1 + \frac{1}{\beta_{\text{cld}}} \right) \sim n_{\text{hot}} k T_{\text{hot}} \left(1 + \frac{1}{\beta_{\text{hot}}} \right),$$

where the subscripts ‘cld’ and ‘hot’ refer to the cool cloud and hot intercloud phases, respectively. This condition fixes the degree of magnetic coupling of clouds to plasma beta values such that

$$1 + \frac{1}{\beta_{\text{cld}}} \sim \frac{n_{\text{hot}} k T_{\text{hot}}}{n_{\text{cld}} k T_{\text{cld}}} \frac{m_p g}{T_{\text{cld}}},$$

where $n_{\text{hot}} \sim \sigma_T n_{\text{hot}} k T_{\text{hot}}$ is the Thomson scattering optical depth of the external hot plasma. The observed high-energy spectra imply $\tau_{\text{hot}} \sim 1$ (e.g. Zdziarski 1995), which is also required for consistency with Eddington-limited quasispherical accretion (Rees 1984).

The condition of pressure equilibrium in a multiphase AGN magnetosphere thus implies a maximum cloud density at which the internal pressure is entirely thermal (i.e. $\beta_{\text{cld}} \gg 1$), with typical parameters implying

$$n_{\text{cld}} \lesssim \frac{n_{\text{hot}}}{\sigma_T} \frac{m_p g}{T_{\text{cld}}} \sim 10^{18} \frac{T_{\text{cld}}}{10^9 \text{K}}^{-1} \left(\frac{r}{10^9 \text{cm}}\right)^{-2} M_{\odot}^{-2} \text{ cm}^{-3}.$$

Beyond this maximum density at which a cloud becomes essentially a field-free or ‘diamagnetic’ plasmoid, the internal cloud pressure exceeds the pressure in the external magnetosphere and hence, confinement is no longer possible.

### 3.1.1 Diamagnetic Effects

When decoupled from an external magnetic field, clouds distort the surrounding field lines and subsequently attain a filamentary structure aligned to the field owing to lateral compression by the restoring magnetic stresses. At the same time, the clouds experience a radial force due to large-scale spatial gradients in the nonuniform field. This force can effectively eject diamagnetic plasmoids from regions of high field strength. The mechanism is often referred to as the ‘melon-seed effect’, since the combined action of magnetic stresses effectively squeezes out a cloud between radial field lines like a melon seed between two fingers (Severny & Khoklova 1953; Schlüter 1957; Parker 1957). This process has been studied in the context of mass ejections from the solar corona (Brueckner 1983; Pneuman 1983).

Under the condition of pressure equilibrium between the diamagnetic cloud and the external, magnetically-dominated medium, the equation of motion is (Brueckner 1983; Pneuman 1983)

$$\frac{d\nu}{dt} = -g \left[ \frac{k T}{m_{\nu} g} \left( \ln \frac{B^2}{B_{\nu}} \right) - 1 \right].$$

For a radially-diverging field, with $B \propto r^{-e}$, the acceleration exceeds gravity when the initial temperature of the plasmoid is higher than the escape temperature $T_{\text{esc}} / T_{\text{vir}} \sim 1 / 2e$. The cool clouds considered here, however, have $T_{\text{esc}} / T_{\text{vir}} < 1$ and the melon-seed effect is unimportant compared with the competing effects of gravity and radiation pressure.

### 3.1.2 Radiation Pressure Effects

The radiative opacity of dense, cool gas can be sufficiently large that small-scale clouds subjected to the powerful radiation field in the central regions of AGN can experience strong volumetric radiation forces (e.g. de Kool & Begelman 1993). These forces result from the momentum imparted by photons that are absorbed and also from the increase in the internal pressure as photons are subsequently created. The bulk acceleration in the cloud rest frame is equivalent to an effective ‘negative gravity’, defined by

$$\frac{g'_{\nu}}{g} \approx \int \frac{d\nu}{\sigma_{\nu}} \frac{L_{\nu}}{\sigma_T T_{\text{Edd}}},$$

where $\sigma_T$ and $\sigma_\nu$ are the scattering and radiative opacities, respectively (we note that $\sigma_T$ reduces to the Klein-Nishina relation at high energies). Since radiation pressure depends on the effective cross-section per particle, the acceleration is only effective over an optically-thin layer. Thus, dense clouds with line of sight column densities $< 10^{20}$ cm$^{-2}$ for which $\sigma_\nu \gg \sigma_T$ can attain very small scaleheights, with $h_{\text{cld}}$ reduced by a factor $g'/g \gg 1$. Such clouds can be prevented from being radiatively driven outward by the tension in field lines. The compressive action of the radiation force against the restoring magnetic tension force then gives rise to thin clouds that are highly favourable for efficient thermal reprocessing of radiation, since a cloud can span a large covering area whilst at the same time maintaining a small volume-filling fraction.

As pointed out by Celotti, Fabian, & Rees (1992), the opacity of dense, optically-thin clouds in the central regions of AGN is expected to be dominated by free-free absorption, which has a cross-section $\sigma_{\nu,ff}^T$ given by

$$\frac{\sigma_{\nu,ff}^T}{\sigma_T} \sim n_{\text{cld}} k T_{\text{cld}} \frac{m_p c^2}{h^3 \nu^3} \left( \frac{k T_{\text{cld}}}{m_e c^2} \right)^{-3/2} \left[ 1 - \exp \left( -\frac{h \nu}{k T_{\text{cld}}} \right) \right].$$

Since the strongest coupling is between the dense gas and low-energy photons, the strongest radiation pressure effects
result from a high brightness temperature radiation field, such as that generated by a synchrotron source. With the presence of strong magnetic fields, the centres of AGN provide a natural environment for such a nonthermal source and the effective gravity of the spectrum of primary radiation which is reprocessed by surrounding Comptonizing particles as well as by an underlying accretion disk if \( T_{\text{abs}} \) is moderate. Clearly, the most disruptive effects occur when \( d \) becomes comparable to or even exceeds the characteristic thickness \( R_{\text{cld}} \) of a cloud. In the present context, it is also particularly important to consider the possibility that \( R_{\text{cld}} \) may be smaller than the effective mean free path for encounters between the hot and cool electrons, in which case a non-diffusive description of the mixing is required.

4 MICROPHYSICAL CONSTRAINTS

A multiphase medium in which cool, dense clouds confined by magnetic fields are immersed in a hot, scattering-dominated plasma cannot be maintained indefinitely. The spatial gradients in both temperature and magnetic field trigger diffusive processes which, despite operating on microphysical scales, can ultimately result in macroscopic effects (see Begelman & McKee 1990). Diffusive mixing acts to restore a multiphase system to a spatially homogeneous and thermally unstable state. Over a timescale \( \Delta t \), diffusion disrupts the boundary layer between phases over an effective depth \( d \sim \sqrt{D\Delta t} \), where \( D \) is the diffusion coefficient.

4.1 Thermal Conduction

The high thermal conductivity of an ambient hot plasma poses the most serious threat to the continued existence of a spatially-distinct cool phase in the form of small-scale dense clouds embedded within it. The cool clouds can be readily penetrated by the hot electrons, so that the two phases assimilate towards a new thermal equilibrium that is either hot or cold, depending on whether the clouds evaporate or whether condensation prevails (Balbus & McKee 1982, McKee & Begelman 1990).

4.1.1 Diffusive vs. Saturated Conduction

In the diffusion approximation to thermal conduction, the classical Spitzer conductivity, \( \kappa \), defines the thermal diffusion coefficient by (see Cowie & McKee 1977).

\[
D_T = \frac{2}{5} \frac{\kappa}{n_{eK}} = \lambda_T v_T
\]

where \( \lambda_T \) is the effective path length between collisions and \( v_T = \left( kT_e / m_e \right)^{1/2} \) is the thermal electron velocity. This formalism is only valid on scales larger than \( \lambda_T \); on smaller scales, a non-diffusive (i.e. collisionless) treatment is necessary (see McKee & Begelman 1990 and references cited therein). The observed high-energy spectra of most AGN suggest that Thomson depths just below unity are compatible with Compton temperatures that can reach up to mildly relativistic values (e.g. Johnson 1994, Zdziarski 1993, Zdziarski, Johnson, & Magdziarz 1996). At such extremely high temperatures, heat-conducting electrons can freely penetrate small-scale inhomogeneities in the form of cool clouds embedded in the magnetosphere. Moreover, the effective path length, \( \lambda_T \), for collisions between the hot electrons and the denser cloud particles is much shorter than the free mean path, \( \lambda_{\text{wdfp}} \), for collisions between the hot electrons themselves, with (Spitzer 1962)

\[
\lambda_T \sim \lambda_{\text{wdfp}} n_{\text{hot}} / n_{\text{cld}} \sim (3 \times 10^3) \left( \frac{n_{\text{cld}}}{10^5 \text{cm}^{-3}} \right)^{-1} \left( \frac{T_{\text{hot}}}{10^8 \text{K}} \right)^2 \text{cm}.
\]

Hot electrons which penetrate dense clouds on scales larger than \( \lambda_T \) readily lose their energy to collisions. Consequently,
the heated clouds can expand and thereby effectively evaporate if the density is below the critical density \( n_{\text{crit}} \) at which the additional heat input can be efficiently radiated away. Relative to the density of the hot electrons, this critical density is

\[
\frac{n_{\text{crit}}}{n_{\text{hot}}} \sim (2 \times 10^6) \left( \frac{T_{\text{hot}}}{10^5 \text{K}} \right)^{-1/2} \left( \frac{T_{\text{hot}}}{10^9 \text{K}} \right)^{-1/2} .
\]

When \( n_{\text{cld}} \gg n_{\text{crit}} \) and radiative cooling dominates Coulomb heating, the energy deposited into clouds is removed faster than a high temperature equilibration can be established. The impenetrating electrons thus remain cool after having lost their energy and thereby effectively condense into the clouds. Hence, the resulting cloud of dense gas maintains a temperature which remains considerably cooler than the surroundings.

As mentioned earlier, the diffusion approximation to thermal conduction breaks down on scales smaller than \( \lambda_T \), since the conducting electrons are unimpeded by collisions. When the hot electrons enter dense clouds with scale heights \( R_{\text{cld}} < \lambda_T \), the energy imparted by dynamical friction effectiv ely produces a uniform heat input throughout the cool gas. This saturated heat conduction also results in cloud evaporation, unless \( n_{\text{cld}} > n_{\text{crit}} \).

### 4.1.2 The Thermal Diffusion Depth

For parameters relevant to the innermost central regions of AGN, the depth to which cool clouds can be penetrated by a diffusive heat flux due to hot electrons during a timescale \( \Delta t \) (in seconds) is

\[
d_T \sim (6 \times 10^5) \left( \frac{n_{\text{cld}}}{10^{18} \text{cm}^{-3}} \right)^{-1/2} \left( \frac{T_{\text{hot}}}{10^9 \text{K}} \right)^{5/4} (\Delta t)^{1/2} \text{cm} ,
\]

Even over a timescale as short as a typical radiative cooling time of the dense gas, with \( t_{\text{rad}} \sim (2 \times 10^{-6}) n_{18} T_5^{-3/2} \text{s} \) for bremsstrahlung emission (where \( n_{18} = n_{\text{cld}}/10^{18} \text{cm}^{-3} \) and \( T_5 = T_{\text{cld}}/10^5 \text{K} \)), this diffusion depth is larger than \( \lambda_T \) by a factor

\[
\frac{d_T}{\lambda_T} \sim 10 \left( \frac{T_{\text{hot}}}{10^9 \text{K}} \right)^{-3/4} \left( \frac{T_{\text{cld}}}{10^5 \text{K}} \right)^{1/4} \left( \frac{\Delta t}{t_{\text{rad}}} \right)^{1/2} .
\]

Thus, the diffusion approximation to thermal conduction is valid over all relevant timescales, \( \Delta t \gtrsim t_{\text{rad}} \) for clouds with thicknesses \( R_{\text{cld}} \gtrsim \lambda_T \). Of these clouds, those with thicknesses \( < d_T \) are obliterated unless \( n_{\text{cld}} > n_{\text{crit}} \) or unless they are decoupled from the field lines to which the hot, conducting electrons are also tied.

If the cloud density is higher than the minimum, \( n_{\text{crit}} \), required for radiative cooling to efficiently remove the extra heat input, then it is possible that clouds can remain relatively cool whilst threaded by field lines to which hot electrons are also tied. When the cloud thickness exceeds \( d_T \), the conducting electrons effectively condense as they infuse into the clouds and lose their energy. At lower densities, however, clouds coupled to the field lines readily evaporate and are thus unable to produce any observable spectral features that can be identified with thermal reprocessing by cool gas. Alternatively, it is possible that clouds are completely decoupled from the field lines frozen into the external plasma. Unless the cool, dense gas and the hot, diffuse plasma are coupled to discrete field lines, such clouds probably manifest themselves as distinct, self-enclosed structures, possibly with a negligible internal magnetic field (\( B_{\text{cld}} \gg 1 \)) if the thermal pressure alone is sufficient to roughly maintain equilibrium with the external magnetosphere.

### 4.1.3 The Suppression of Thermal Diffusion

Regardless of how they are coupled to the ambient magnetosphere, dense clouds are expected to be thermally decoupled from the external conducting plasma in directions perpendicular to \( B \), where the random motion of hot electrons is strongly impeded by gyration. Thermal conduction in this transverse direction is attenuated by a factor (1+\( \Omega_e^2/\nu_{\text{coll}}^2 \))^{-1} (Chapman & Cowling 1952), where \( \Omega_e/\nu_{\text{coll}} \) is the ratio of the electron gyrofrequency to the mean collision frequency.

In the central magnetospheres of AGN, field strengths which are in equipartition with the radiation energy density are typically \( \sim 10^4 \) G (e.g. Rees 1984), which gives

\[
\frac{\nu_{\text{coll}}}{\Omega_e} \sim (4 \times 10^{-5}) B_4^{-1} n_{18}^{-1/3} T_5^{-2} \left( \frac{T_{\text{hot}}}{10^9 \text{K}} \right)^{-3/2} ,
\]

where \( B_4 = B/10^4 \) G. In spite of the extremely high cloud densities, these field strengths are sufficient to appreciably suppress collisions across the confining field lines. Diffusion still occurs over the relevant timescales, since this ratio implies that roughly \( 10^6 r_{\text{cld}}^{1/2} \gg \nu_{\text{coll}}^{-3/2} \) collisions can take place during the radiative lifetime of the dense gas. However, the corresponding transverse diffusion distance is negligible compared to \( d_T \) for diffusion along the field lines owing to the strongly channeled motion of the hot electrons along the lines of force.

Magnetic fields therefore play two crucial roles in a magnetosphere composed of multiple coexisting phases, providing a confinement mechanism for spatially-localized regions of cool gas and also effectively insulating such clouds from the normal transport of thermal energy from the ambient hot plasma. As we will explain in the following, however, there is an additional and more direct means by which heat can be injected into cool clouds in the central regions of AGN that is independent of the presence of field lines.

### 4.1.4 Pair Plasma Effects

Heat injection by electron-positron (\( e^+e^- \)) pairs is a particularly important consideration for the survival of cool, dense clouds in the compact environments at the centres of AGN. This is because once the compactness parameter \( l \equiv \sigma_T L / n_{\text{cld}} c^3 R \) satisfies \( f_c l > 47 \), where \( f_c \) is the fraction of primary luminosity that is emitted above 1 MeV, the encounters between \( \gamma \)-ray photons which produce pairs can occur anywhere - even within clouds themselves. Thus, the pair balance the entire source region, filling up the magnetosphere in which the primary radiation is generated, and can equally affect all clouds, regardless of how they are coupled to the field lines.

Thermal \( e^+e^- \) pairs are expected to constitute an additional component of the hot plasma phase which maintains Compton equilibrium at roughly the same temperature as the ambient electron-ion plasma component. However, even when \( L \ll L_{\text{Edd}} \), the scattering off the extra pairs lowers the effective Eddington limit, so that the hot plasma may be blown...
outward by the radiation pressure from the Thomson scattering of ambient photons (see Lightman, Zdziarski, & Rees 1987). Because of annihilation, on the other hand, the lifetime of $e^+e^-$ can be quite short when $l$ is large, since the timescale is typically $t_{\text{ann}} \sim (r/c)^{-1}$, where the Thomson scattering pair depth is $\tau_{\text{pair}} \sim (f_{\text{scat}}/\pi)^{1/2}$ under steady-state conditions (Guilbert, Fabian, & Rees 1983).

The conductive properties of hot, thermal $e^+e^-$ are essentially the same as that of electrons in an ordinary hot plasma at the same Compton temperature, so that pairs created ‘in situ’ can provide a heat input into cool clouds. For pairs created inside the clouds, however, the heat injection cannot adequately be described as necessarily either diffusive or saturated conduction, since a roughly uniform heat input can be provided before the pairs annihilate.

Energetic charged particles which enter or, in the case of pairs, are created within a plasma of lower thermal energy slow down due to long-range Coulomb interactions. Extensive studies of solar flares have shown that the rate at which this thermalization occurs is always much faster than the rate at which positrons annihilate (e.g. Crannell et al. 1976 and references cited therein). If $\Delta E \sim 1$ MeV) is the total energy lost by pairs due to collisions with cool, dense cloud particles, then the minimum volume heating rate is $n_{\text{cld}} \sigma_{\text{cld}} \Delta E$, where $n_{\text{pair}}$ is the pair density. The corresponding minimum cloud density at which this extra heat input can be balanced by radiative cooling is then

$$n_{\text{cld}} > A \times 10^{27}$$

$$\tau_{\text{pair}} \Delta E \sim m_{\text{e}} c^2 \left( \frac{T_{\text{cld}}}{10^{5} \text{K}} \right)^{-1/2} \left( \frac{r}{10^8} \right)^{-1} M^{-1} \text{cm}^{-3}.$$  

At these high densities, clouds in which hot, thermal $e^+e^-$ are created can maintain cool temperatures relative to the surroundings by efficiently radiating away the energy imparted by the pairs. At lower densities, cloud evaporation is inevitable. Once thermalized, the cool pairs quickly annihilate, at a rate which exceeds $n_{\text{cld}} \sigma_{\text{cld}}$ by a Coulomb correction factor that is roughly an order of magnitude at $\sim 10^7$ K (see Crannell et al. 1976).

### 4.2 Magnetic Diffusion and Kelvin-Helmholtz Effects

We have shown above that in the magnetospheres of AGN, the motion of hot electrons is channelled so strongly that their diffusion across the field lines is essentially negligible, despite the extremely high densities of cool clouds confined by the field. It would therefore seem that magnetic diffusion may not necessarily pose a too serious threat to the survival of such clouds embedded in AGN magnetospheres. However, it is possible that non-collisional processes (e.g. turbulence, local fluctuations) trigger events which can ultimately lead to the enhanced diffusion of field lines into very dense (and essentially field-free) clouds. Of particular relevance to the central regions of AGN, where strong dynamical effects are important, is the hydromagnetic Kevin-Helmholtz instability, which we consider here.

Clouds of dense gas moving relative to an external, magnetically-dominated medium (i.e. with $v_{\text{cld}} \sim v_A$) are susceptible to disruption by enhanced diffusion due to the Kelvin-Helmholtz (KH) instability (see Arons & Lea 1980 and references cited therein). This instability is triggered by hydromagnetic turbulence which forms in a layer between the sheared phases and which fragments the clouds, thereby effectively increasing the surface area over which microphysical diffusion operates. The turbulent mixing of the phases which ensues can then assimilate the small-scale clouds much more rapidly than collisions. The instability is particularly destructive to unmagnetized clouds, since clouds which contain an internal magnetic field (with $\beta_{\text{cld}} > \beta_{\text{hot}}$) are further required to undergo some small-scale reconnection with the diffusing field lines for the phases to be thoroughly mixed, so that the timescale for disruption by the KH instability is expected to be longer for magnetized clouds than for unmagnetized clouds.

The linear growth rate of the KH instability for dense, unmagnetized clouds moving at a velocity $v_{\text{cld}}$ with respect to an external hot, magnetically-dominated medium is

$$\gamma_{KH} = \left[ (k_{\parallel} v_{\text{cld}})^2 - k_{\perp}^2 v_A^2 \right]^{1/2} \left( \frac{n_{\text{hot}}}{n_{\text{cld}}} \right)^{1/2},$$

where $k_{\parallel} = k \cos \theta$ is the component of the perturbation wavevector $k$ that is parallel to the external magnetic field $B$. The instability can disrupt moving clouds if the characteristic timescale for the modes to grow, $t_{KH} \sim 1/\gamma_{KH}$, is shorter than the cloud sound-crossing response timescale, $t_{s,cld} \sim R_{cld}/v_{s,cld}$. Since the most disruptive perturbations are those with $k R_{cld} \gtrsim 1$, this condition for instability is equivalent to

$$\frac{v_{\text{cld}}}{v_A} \gtrsim 1,$$

where we have used the pressure equilibrium condition, $v_{s,cld} \sim v_A \sqrt{n_{\text{hot}}/n_{\text{cld}}}^{1/2}$.

Since $v_{\text{cld}}/v_A \sim n_{\text{hot}}/n_{\text{cld}} \lesssim 1$, clouds accreting towards the central mass in AGN become only marginally unstable in the absence of dynamical forces other than gravity. If the clouds experience a net acceleration $g^* > g$ due to radiation pressure force, then the resulting velocity that can be attained is much larger than $v_H$ and the clouds become unstable to KH effects.

Once the KH instability is triggered, it very quickly reaches a nonlinear regime in which the clouds suffer a cascade of fragmentation, with the enhanced microphysical diffusion processes ultimately sealing their fate. Because these destructive effects would occur very rapidly, clouds which are essentially field-free would be rare unless they were being formed at a much faster rate than clouds coupled to field lines.

### 5 THE PARAMETER SPACE FOR CLOUD THICKNESSES

We now examine how the various physical constraints on cloud thicknesses determined in the previous sections compare with each other by plotting the quantities calculated for a range of cloud densities and for a set of parameters which are representative of the innermost central regions of AGN. Under the condition of pressure equilibrium at the boundary between cool, dense clouds and a hot, magnetically-dominated intercloud plasma, the cloud plasma beta can be eliminated systematically throughout the above equations by being replaced with...
Figure 2. Parameter space for cool, dense clouds in a central AGN magnetosphere, indicating the densities and thicknesses for which magnetically-confined clouds can survive in the presence of global dynamical and microphysical processes. The cloud temperature is $T_{\text{cld}} = 10^9$ K and the hot intercloud gas has a temperature $T_{\text{hot}} = 10^9$ K and a Thomson scattering optical depth $\tau_{\text{hot}} = 1$. The compactness parameter of the source region is $l \sim 230$. The darkest shaded region indicates where cool, dense gas always persists. The next darkest shaded region in the plot indicates where the magnetic field can suppress transverse conductivity for the parameter range of interest.

The darkest shaded region in the plot indicates where radiative cooling dominates over all other microphysical processes. Thus, any additional heating due to thermal conduction which takes place in clouds at these densities can be efficiently radiated away and cool, dense gas always persists. The next darkest shaded region in the plot indicates where clouds threaded by the same field lines to which hot gas is connected suffer Coulomb heating before the pairs annihilate unless their density is higher than about $10^{16}$ cm$^{-3}$, when radiative cooling becomes effective.

The parameter space plot ($n_{\text{cld}}$ vs. $R_{\text{cld}}$) for cloud thicknesses shows regions that are restricted by the following relevant constraints: the maximum thickness, $t_{\text{ff}}$, allowed for pressure support on a dynamical free-fall timescale (upper heavy line); the pressure scaleheight, $h$, for confinement by gravity and magnetic stresses (dashed line); the microphysical limit $d_T$ (dotted lines) due to thermal diffusion calculated for a free-fall timescale, $t_{\text{ff}}$, and for a radiative cooling timescale, $t_{\text{rad}}$, as indicated in the plot; and the effective path length $\lambda_T$ over which collisions are effective.

The diffusion depth $d_{T,\perp}(t_{\text{ff}})$ for thermal conduction transverse to magnetic field lines calculated for a free-fall time is also shown. A direct comparison with $d_T(t_{\text{ff}})$ for thermal diffusion along the field lines demonstrates the degree to which the magnetic field can suppress transverse conductivity for the parameter range of interest.

Also shown is the diffusion depth $d_{\text{pair}}$ (dot-dot-dot-dash line) for thermal pairs along magnetic field lines. This is the same as $d_T$, but calculated for an annihilation timescale $t_{\text{ann}} \sim \tau_{\text{cld}}(t_{\text{ff}})$ for cloud thicknesses for which hot gas always persists. The next darkest shaded region in the plot indicates where radiative cooling dominates over all other microphysical processes. Thus, any additional heating due to thermal conduction which takes place in clouds at these densities can be efficiently radiated away and cool, dense gas always persists. The darkest shaded region in the plot indicates where radiative cooling dominates over all other microphysical processes. Thus, any additional heating due to thermal conduction which takes place in clouds at these densities can be efficiently radiated away and cool, dense gas always persists.
substantially reduced and hot electrons can then readily diffuse into dense clouds on timescales shorter than $t_{ff}$. Thus, such clouds can only survive if coupled to separate field lines or as self-contained structures, decoupled from the magnetosphere.

6 SUMMARY AND CONCLUSIONS

In light of the mounting observational evidence that thermal reprocessing plays a crucial role in the central regions of AGN, we have presented a detailed examination of the possibility that cool, thin clouds coexist with hot plasma in a central magnetosphere where the primary radiation is generated. The thermalization and cooling timescales in these central regions are sufficiently short compared to the global free-fall timescale that thermal reprocessing of this primary radiation is inevitable. Similarly, relatively short sound-crossing times imply that pressure equilibrium between multiple co-existing phases can be readily established. The strong gravitational, magnetic and radiation forces in the central regions of AGN can then confine spatially-localized regions of gas that is much denser and cooler than the surrounding, magnetically-dominated plasma. The thicknesses that can then be achieved are extremely small by most astrophysical standards.

The observational relevance of thin clouds with such physical properties clearly depends on whether they can survive the effects of microphysical diffusion processes for at least a few radiative timescales during which they can produce thermal reprocessing signatures in the spectra. We have summarized the relevant effects in a parameter space diagram which encompasses the range of cloud densities over which radiative cooling is important.

Our results indicate that thermal diffusion along the field lines is the most serious effect, since the diffusion distances approach the cloud pressure scaleheight on timescales much shorter than the free-fall time. This implies that on scales larger than the effective path length between collisions, clouds that are coupled to the same field lines to which hot electrons are also tied must be continuously regenerated over timescales shorter than the free-fall time.

Evaporation is also the fate of most clouds with thicknesses smaller than the collision path length, since then saturated (non-diffusive) conduction is effective. Furthermore, conduction by electron-positron pairs effectively precludes all clouds with densities below $\sim 10^{16} \text{ cm}^{-3}$, since radiative cooling cannot then compete with the heating due to encounters between the pairs and the cloud particles.

Despite the extremely high densities of the clouds, our results show that the motion of heat-conducting electrons across the lines of forces, dragging the field lines with them, can still be strongly suppressed. Cool clouds can thus remain thermally decoupled from the external hot plasma in directions transverse to the magnetic field. The diffusion of field lines is then only likely to pose a threat to very dense clouds which experience a net bulk acceleration due to radiative or large-scale magnetic forces and which are consequently susceptible to turbulent diffusion through the Kelvin-Helmholtz instability. Therefore, the clouds most able to reprocess a substantial amount of radiation and survive against this enhanced diffusion of field lines are those which are confined by field lines that are sufficiently tangled to prevent significant bulk motion.

Our results indicate that the most favourable region in the cloud parameter space lies in the extreme high-density limit, where radiative cooling dominates all other microphysical process. This subspace spans a density range $\sim (10^{17} - 10^{18}) \text{ cm}^{-3}$ and a thickness range extending from $\sim 10^{6}$ cm down to microphysical scales determined by magnetic diffusion. In this parameter regime, clouds can still be affected by thermal conduction along the field lines, but the heat input is efficiently radiated away so that the hot electrons effectively condense into the clouds and cool, dense gas always prevails. This gas is therefore capable of producing distinct thermal reprocessing signatures.

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