The Cloudy Universe

Mark Walker & Mark Wardle

Special Research Centre for Theoretical Astrophysics, School of Physics,
University of Sydney, NSW 2006
M.Walker/M.Wardle@physics.usyd.edu.au

Abstract

Modelling of Extreme Scattering Events suggests that the Galaxy's dark matter is an undetected population of cold, AU-sized, planetary-mass gas clouds. None of the direct observational constraints on this picture – thermal/non-thermal emission, extinction and lensing – are problematic. The theoretical situation is less comfortable, but still satisfactory. Galactic clouds can survive in their current condition for billions of years, but we do not have a firm description for either their origin or their evolution to the present epoch. We hypothesise that the proto-clouds formed during the quark-hadron phase transition, thereby introducing the inhomogeneity necessary for compatibility with light element nucleosynthesis in a purely baryonic universe. We outline the prospects for directly detecting the inferred cloud population. The most promising signatures are cosmic-ray-induced Hα emission from clouds in the solar neighbourhood, optical and X-ray flashes arising from cloud-cloud collisions, ultraviolet extinction, and three varieties of lensing phenomena.

Keywords: dark matter — galaxies: halos — ISM: clouds

1 Introduction

This paper traces some lines of thought concerning the nature of dark matter which the authors have been pursuing for the last year or so. For the most part its content follows the talk given by one of us (Mark I) to the July 1998 Meeting of the Astronomical Society of Australia in Adelaide, with some extra material reflecting subsequent developments.

We begin with a brief overview of current activity directed towards identifying dark matter (§2), then focus on a model in which the Galactic dark matter is composed of planetary-mass gas clouds — a picture that can be drawn directly from the radio-wave lensing of quasars reported by Fiedler et al (1987, 1994). A lensing event (Extreme Scattering Event, or ESE) occurs when a cloud in the Galactic halo crosses the line of sight: radio waves are refracted by an ionised wind which is evaporated from the neutral cloud by UV radiation (§3). The observed event rate implies that the total mass in clouds is comparable to that of the Galactic dark matter.

This inferred population of $\sim 10^{15}$ cold clouds, each of mass $\sim 10^{-4}$ $M_\odot$ and size $\sim$ AU, suprisingly, does not violate existing observational constraints (§4). The theoretical issues raised by this scenario, discussed in §5, are quite basic: how did the clouds form, and how have they survived? In §6 we consider other techniques for detecting the cloud population. The most promising signatures are optical flashes from cloud collisions, Hα emission from nearby clouds, and various lensing phenomena. Finally, the outlook for the model is discussed in §7.

2 Identification of dark matter

Zwicky (1933) was the first to infer the existence of large quantities of unseen mass, in studies of the dynamics of clusters of galaxies, but it was many years before the "missing mass", or dark matter, problem was widely recognised. Van den Bergh (1999) reviews the early history of this subject, while Ashman (1992) gives a thorough account of the problem in the context of galaxies. It is, in fact, HI galaxy rotation curves which provide the best evidence we have for the existence of dark matter; here the dynamical interpretation, and its implication, is entirely unambiguous. Equally interesting, though less clear-cut, are the indications that the Universe as a whole is composed principally of dark matter — this evidence is discussed extensively by Peebles (1993).

Because stars usually contribute the bulk of the visible mass, at least in galaxies, much attention has been given to the possibility that dark matter is composed of stars which are of low luminosity. This category includes: low-mass main-sequence stars; brown dwarfs; old white dwarfs; neutron stars; and black holes — a diverse group which has required a variety of techniques to constrain their total mass contribution. It is beyond the scope of this paper to summarise these efforts; good reviews are given by Trimble (1987), Ashman (1992) and Carr (1994). However, a unifying feature of this group is that they are all rather dense objects and so constitute strong gravitational lenses even when they are in the halo of our Galaxy. As pointed out by Paczyński (1986), this enables indirect searches for such objects via photometric monitoring of millions of Magellanic cloud stars, and such gravitational lensing events have now clearly been detected (Alcock et al 1997). It is not currently known whether these lensing events are caused by dark matter, or by known stellar populations associated with the Galaxy and the Magellanic Clouds (Sahu 1994).

If it turns out that stars don't fit the bill, what might the dark matter be composed of? The lack of success of very deep searches for previously uncatalogued material, conducted with the most modern instrumentation, across the whole range of the observable spectrum, promoted the suspicion that dark matter has *no* electromagnetic interaction. In this case one imagines the dark matter to be composed of massive neutrinos, for example, or perhaps an elementary particle which has not yet been detected? This idea was strengthened by detailed computations of the abundances of light elements which result from primordial nucleosynthesis in a hot Big Bang cosmology. These calculations, when compared to the observed abundances, suggest that only a small fraction of the closure density is in the form of baryonic (ordinary) material — see the review by Schramm & Turner (1998). This picture of weakly interacting dark matter readily lends itself to numerical simulations of the growth of structure (galaxies, clusters, superclusters), from an initially near-homogeneous universe. These simulations demonstrate that dynamically 'cold' dark matter can reproduce the observed structural characteristics of the Universe, at least approximately, while simultaneously remaining consistent with measurements of the Cosmic Microwave Background (CMB) anisotropies. 'Hot' dark matter gives a much poorer representation of the observed structure (Davis et al 1985), suggesting that the dark matter is not composed of neutrinos, but is a type of particle which has yet to be detected. These results have given impetus to a variety of experiments designed to detect individual dark matter particles, or their decay products — see the many contributions to Spooner (1997).

Contrary to these general trends in the field, Pfenniger, Combes & Martinet (1994: PCM94 hereafter) advanced the view that the dark matter associated with galaxies might be composed of cold gas clouds. PCM94 motivated this suggestion with arguments related to galaxy dynamics and evolution, emphasising the astrophysical appeal of dark matter in this form, and noting that if the temperature of the cold gas were close to that of the CMB then the clouds would be very difficult to detect (see also Combes & Pfenniger 1997). PCM94 additionally proposed that the

cold gas should have a fractal structure – an idea which was developed in Pfenniger & Combes (1994) – and that it should be distributed in a thin disk. However, neither of these are essential features for a dark matter model based on cold gas, and one can equally well imagine a spherical halo of individual or clustered clouds (de Paolis et al 1995; Gerhard & Silk 1996). These quasi-spherical distributions of dark matter are more palatable to most dynamicists than highly flattened distributions, but even so there remain plenty of contentious issues relating to the physics of the putative cold gas clouds; these are addressed in §§4,5; first we turn to the main observational evidence for their existence.

3 Extreme Scattering Events

"Extreme Scattering Events" (ESEs) were discovered more than a decade ago (Fiedler et al 1987), during a multi-year program to monitor the positions and radio fluxes of a large number of compact quasars. The events themselves amount to large, frequency-dependent variations in the received radio signal, lasting for a month or two. These variations were immediately recognised as a Galactic lensing phenomenon (Fiedler et al 1987; Romani, Blandford & Cordes 1987), rather than being attributable to intrinsic changes in the source. Each lens is in this case just a localised over-density of ionised gas, which refracts the radio-waves, and flux variations occur when a lens crosses the line-of-sight. The lenses are inferred to be a few AU in radius. In the decade following their discovery there was little progress in understanding the physical nature of these lenses; the possibility of generating high electron densities within interstellar shock waves had been explored (e.g. Clegg, Chernoff & Cordes 1988), but without much success in reproducing the observed light-curves. A particular difficulty with the physics of the early models is that the pressure of the ionised gas is a thousand times larger than that of the diffuse interstellar medium, so the latter cannot confine the former and such a lens ought to explode, lasting only a year or so. In order to avoid this, while still maintaining a static lens, one is forced to resort to some contrivance with magnetic fields or highly elongated lenses.

Motivated by a desire for a simpler explanation, we investigated a specific physical picture for the lenses in which the hot gas is not static but, rather, forms a continuous outflowing wind (Walker & Wardle 1998a). In turn this implies a reservoir of neutral material at the base of the wind, and to ensure longevity of the lens we assumed this (cold) neutral cloud to be in hydrostatic equilibrium, with its thermal pressure balanced by self-gravity. This turns out to offer a good model for the ESEs: a cold, neutral gas cloud in the Galactic halo is expected to develop a photo-evaporated wind as a consequence of the ionising radiation field arising from hot stars in the Galactic disk (Dyson 1968; see also Henriksen & Widrow 1995); the intensity of this radiation naturally generates the requisite density of ionised gas. Moreover the computed light curves, both at low and high radio frequencies, readily reproduce those of the archetypal ESE in the source 0954+658. Indeed as a model for the ESE phenomenon there seem to be no real difficulties with this picture.

However, it follows from the ESE rate (Fiedler et al 1994), in the context of this physical model, that the neutral gas clouds constitute a large fraction of the mass of the Galaxy. In other words, since they are not present in our current inventories of visible matter, they are a major component of dark matter. This conclusion immediately prompts concerns: is this model consistent with other data? What about the constraints from Big Bang nucleosynthesis? How could such clouds form? How can they survive for so long? The next sections address these issues.

4 Compatibility with other data

In order that the mass in neutral gas clouds not exceed the dynamically determined value (i.e that deduced from the rotation curve) for the Galaxy, the individual cloud masses must be very small: $M < 10^{-3}$ M$_\odot$. Assuming cloud masses comparable to this limit, and radii of a few AU implies that they have internal densities $n \sim 10^{12}$ cm^{-3}, very dense in comparison with any other component of the interstellar medium. Three-body reactions (e.g. $3\,\mathrm{H} \rightarrow \mathrm{H} + \mathrm{H}_2$; Palla, Salpeter & Stahler 1983) consequently proceed rapidly and the hydrogen is expected to be in molecular form.

Unfortunately there is very little else that one can deduce *a priori* about the putative neutral gas clouds, and it is necessary to contemplate a broad range of possibilities. With this in mind we now address the issue of detectability of the clouds themselves: ought they to be manifest in other ways?

4.1 Thermal emission

The most obvious expectation of the model is that there ought to be thermal emission from these dense clouds, and the Galactic population as a whole should therefore introduce an extra background of thermal radiation. The expected background spectrum is dictated by the temperature, density and composition of the clouds; we know that the temperature is low, and the density high, but the cloud chemistry is poorly constrained. We can nevertheless arrive at some crude estimates as follows.

Let us approximate any line emission as optically thick within the Doppler core, of velocity width c_s, implying a brightness temperature equal to the kinetic temperature (T) of the cloud, with negligible optical depth (and therefore brightness temperature) outside this region. When viewed as a background – i.e. without resolving the individual clouds – the observed brightness temperature contribution at line centre is then $\Delta T_B \simeq f T (c_s/\sigma)$, where f is the fraction of the sky covered by clouds, and σ is their velocity dispersion. The quasar monitoring data (Fiedler et al 1994) suggest that $f \sim 5 \times 10^{-3}$, while $c_s \ll \sigma \sim 150$ km s^{-1}, and we see that ΔT_B is very small. If the instrument we are using cannot resolve the line (i.e. $2\times$ the channel width is greater than σ), then the recorded brightness temperature perturbation is even smaller: $\Delta T_B \sim \mathcal{R} T^{3/2}$ nK, in a single spectral channel, where $\mathcal{R}$ is the spectral resolving power and T is in Kelvin. Inserting parameters appropriate to the COBE FIRAS instrument, which had brightness temperature sensitivity of order 0.1 mK, and $\mathcal{R} \sim 10^2$ (Fixsen et al 1994) we see that FIRAS would not have detected the line unless $T \gtrsim 100$ K. The foregoing discussion is straightforwardly extended to a small number of spectral lines. While these estimates are rather crude they are not specific to any particular coolant: the key point is that the microwave/FIR data give only weak limits on possible cloud temperatures if there is negligible continuum opacity.

The limits on broad-band radiation are much more restrictive. COBE FIRAS data revealed a Galactic component of continuum emission which could be interpreted in terms of dust with temperatures in the range 4–7 K, and mean optical depth $\langle\tau\rangle \sim 10^{-4}$ (at $\lambda = 0.33$ mm) at high latitude (Reach et al 1995; see Lagache et al 1998 for an alternative interpretation). In the cold cloud model $\langle\tau\rangle = f\,\tau$, where τ is the optical depth of a single cloud. Requiring the thermal continuum emission from any cloud population to be smaller than the COBE measurements, we then demand $\tau < 2 \times 10^{-2}$ if $T = 7$ K, say. (Using the smaller value of f, i.e. f_{coll}, derived in §5.4, this limit relaxes to $\tau < 0.5$.) In turn, this limit on the optical depth implies that the clouds contain essentially no dispersed dust. This is expected if their composition reflects the standard Big Bang abundances, and likely even if the clouds do contain metals, because any dust grains

will settle into the centre of the cloud, forming a "dirty snowball" there. In §5.3 we shall present theoretical arguments that there *must* in fact be some continuum opacity in these clouds – not from dust as such, but from particles of solid hydrogen. The limit on τ just quoted applies equally well to these particles.

4.2 Non-thermal emission

The most striking feature of the γ-ray sky is the luminous interstellar medium in the Galactic plane. This emission arises as a consequence of cosmic rays interacting with the gas, principally by nuclear interactions (i.e. cosmic-ray protons + target nuclei) leading to pion production, with subsequent decay ($\pi^0 \rightarrow 2\gamma$); relativistic electron bremsstrahlung also contributes (e.g. Bloemen 1989). If we suppose that the dark matter is simply cold gas then it too will be luminous in γ-rays, as a result of these processes (de Paolis et al 1995). In principle this provides a strong constraint on the amount of dark matter in cold gas, but in practice the constraint is quite weak because the Galactic distribution of cosmic rays is poorly known; in particular the scale-height of the cosmic ray disk of the Galaxy is uncertain (Webber, Lee & Gupta 1992). In addition the column density of individual dark clouds may be sufficiently high that they are not entirely transparent to γ-rays and cosmic rays. As a result of this freedom in modelling, the γ-ray data must be regarded as inconclusive at present. However, we note that Dixon et al (1998) discovered an unmodelled Galactic "halo" component in the γ-ray background, and the simplest explanation for this is that it is due to unseen (cold, dense) gas.

In addition to cosmic rays interacting within each cloud, we have already noted (§3) that UV photons are absorbed by the cloud and drive a wind from its surface. Radiation from this wind, in particular the optical/IR line transitions of molecular and atomic hydrogen, might be detectable. (This is, of course, thermal emission, but it seems more appropriate to cover it here than in §4.1 because the wind is so much hotter than the underlying cloud.) Noting that the Galactic halo ionising radiation has an intensity of order $2 \times 10^6/\pi$ cm^{-2} s^{-1} sr^{-1} (Dove & Shull 1994), and that all of the ionising photons incident upon a cloud will be absorbed, one can estimate (e.g. Bland-Hawthorn & Maloney 1997) that each cloud should have an Emission Measure of EM ~ 2 pc cm^{-6}. Averaging over the population of clouds, which collectively cover only a small fraction of the sky, then leads to a mean surface brightness (EM) a factor $f \sim 5 \times 10^{-3}$ smaller. This emission therefore contributes a tiny fraction ($\sim$1%) of the observed EM at high Galactic latitudes (Reynolds 1992), and the data do not currently provide strong limits on the proposed cloud population. This situation could be improved with studies of the low-level emission-line wings, as the clouds are expected to have a velocity dispersion ($\sigma \simeq 150$ km s^{-1}) which is much greater than the width of the dominant observed component.

We can also consider the possibility of detecting individual clouds passing through regions where the radiation field is high, i.e HII regions, but the prospects seem remote. Here we differ from the conclusions of Gerhard & Silk (1996), who considered clouds having radii some four orders of magnitude larger (hence solid angles, and Hα fluxes, eight orders of magnitude larger) than in our model.

4.3 Extinction events

If the Galactic dark matter is composed of clouds which cover a fraction $f \sim 5 \times 10^{-3}$ of the sky then, because the total column of dark matter is known from dynamics (e.g. Binney & Tremaine 1987) to be ~ 100 M$_\odot$, one can immediately infer that the column density of each cloud is $N \sim 10^{24}$ cm^{-2}. If these clouds followed the same relationship between extinction and column

density as the known molecular gas in the Galaxy, this would correspond to several hundred magnitudes of visual extinction; in turn this would mean that 0.5% of extragalactic stars (e.g. in the LMC) would be completely extinguished, with these events lasting tens of days. This phenomenon is readily detectable but has not been reported, and we are obliged to conclude that the clouds cannot be suffused with dust (see also §4.1).

In the UV – X-ray bands each cloud must be opaque because the fundamental constituents (H_2 and He) themselves provide substantial opacities in these regions of the spectrum (cf. Combes & Pfenniger 1997). The main sources of opacity are: Rayleigh scattering (near UV); the Lyman and Werner transitions of H_2; photoelectric absorption; and electron scattering at high energies. Monitoring extragalactic sources in these wavebands should, therefore, unambiguously reveal the presence of such a cloud population via the extinction events they introduce. Insufficient data have been recorded to date to usefully constrain a cold-cloud population, so this remains an interesting experiment for the future.

4.4 Lensing events

There are several distinct phenomena, relevant to cold clouds, which fall under the general heading of "lensing": plasma lensing (refraction by ionised gas, giving rise to ESEs), gas lensing (refraction by neutral gas), and gravitational lensing (refraction by the gravitational field). The last of these is widely acknowledged as a tool for investigating dark matter, and it is appropriate to deal with it first.

4.4.1 Gravitational lensing

Searches for gravitational microlensing of stars in the Large Magellanic Cloud (e.g. Alcock et al 1997) are designed to detect flux increases of 30% or more, and consequently these experiments are sensitive only to strong gravitational lenses, i.e. objects with column density of 10^4 g cm^{-2} or greater. This is very much greater than the column density inferred for the cold clouds ($\sim 10^2$ g cm^{-2}; see §5.4), and so the limits on low mass MACHOs in the Galactic halo (Alcock et al 1998) are, by definition, irrelevant, even though they cover the critical planetary mass range.

Clouds located at greater distances, e.g. at cosmological distances, may be strong gravitational lenses because the column density required to make a strong lens is smaller in this case, and we expect that quasars will be gravitationally microlensed by intervening clouds. Several authors have argued that quasars are indeed microlensed by planetary-mass objects, including lensing of quasars by cosmologically distributed objects (Hawkins 1993, 1996), and microlensing of quasars which are *macro*lensed by foreground galaxies (e.g. Schild 1996). The evidence is equivocal at present, and there is a pressing need to clarify this situation; clarification could be achieved by monitoring quasars which are viewed through the halos of low redshift galaxies or clusters (Walker 1999a; Walker & Ireland 1995; Tadros, Warren & Hewett 1998). Notice that if Hawkins is correct, that all quasars exhibit variability as a consequence of microlensing by planetary mass objects, then it follows (Press & Gunn 1973) that a large fraction of the cosmological critical density is in the form of these lenses. This has implications for cosmic nucleosynthesis (§5.1) and, in turn, the origin of the clouds (§5.2).

4.4.2 Gas lensing

The concept of "gas lensing" was introduced by Draine (1998), who pointed out that the refractive index of neutral hydrogen/helium gas clouds would be interestingly large if they had the mass and radius proposed by Walker & Wardle (1998a). More specifically: the refractive index could

be comparable to the angular size of Galactic clouds, implying that strong focussing/de-focussing might occur. Supposing that no such effects are manifest in the microlensing monitoring data for the Magellanic Clouds (cf. Alcock et al 1998), Draine (1998) then used this concept to restrict the acceptable combinations of cloud masses and radii, under assumed polytropic equations of state. The principal difficulty in applying this work is our current lack of information on the density profile of the individual clouds. In turn this reflects our primitive understanding of the physics relevant to these clouds (particularly the heating/cooling balance: §5.3).

4.4.3 Plasma lensing

In §3 we presented the arguments which lead from the observation of ESEs to the conclusion that the dark matter is composed of cold clouds. The ESE phenomenon is, however, not the only piece of evidence which points to the existence of a large population of dense plasma clouds — this population is also revealed by observations of periodic fringes in the spectra of pulsars (Rickett 1990). These periodicities were discovered many years before ESEs, and their interpretation requires similarly dense clouds of ionised gas, a few AU in radius. In principle these observations of pulsars are much more informative, in respect of the plasma lenses, than observations of ESEs in quasars, but this advantage has not yet been exploited. Pulsars clearly offer an opportunity to greatly advance our understanding of the ionised gas clouds responsible for ESEs, but this requires systematic studies of the various multiple imaging phenomena.

5 Theoretical considerations

In §4 we described the immediate observational implications of a population of cold gas clouds contributing to the dark matter; it is important to recognise that none of these considerations excludes the model proposed in §3. We now turn to issues which are more theoretical, in the sense that they relate primarily to the physics of the putative clouds.

5.1 Cosmology

Theoretical cosmology is responsible for establishing the idea that dark matter is principally non-baryonic. This idea rests on two distinct lines of evidence, relating to primordial nucleosynthesis and to the formation of structure in the Universe.

When the Universe was only minutes old (redshift $z \sim 10^9$), it passed through a period where nuclear reactions were effective in building-up the abundances of light elements from the initial building blocks of protons and neutrons. If the Universe is assumed to be homogeneous then the abundances of the various elements can be calculated with some precision, subject only to the unknown photon/baryon ratio (or equivalently the baryonic contribution, Ω_B, to the closure parameter Ω). For a small range of values $0.005 \lesssim \Omega_B \lesssim 0.03$, the calculated abundances of the light elements are roughly in accord with the observed abundances, giving confidence in the model and admitting an estimate of Ω_B — see Schramm & Turner (1998). When combined with other pieces of evidence that indicate $0.1 \lesssim \Omega \lesssim 1$ (e.g. Peebles 1993), these calculations demonstrate that most of the Universe (i.e. the dark matter) was not in the form of smoothly distributed baryons at the time of nucleosynthesis. This conclusion is usually stated more succinctly as a requirement for non-baryonic dark matter.

The second line of evidence for non-baryonic dark matter relates to the theory of growth of structure in the Universe. The fact that the Cosmic Microwave Background (CMB) is smooth to

10^{-5} K on large scales (Smoot et al 1992) tells us that the diffuse baryons possessed very little large-scale inhomogeneity at the epoch when electrons recombined with ions to form neutral atoms (at $z \simeq 1500$). But today we see a great deal of structure: galaxies, clusters and even superclusters of galaxies appear organised in a network of vast filamentary features. This proliferation of structure can be explained by the effects of gravity acting on primordial (adiabatic) density fluctuations if the dark matter couples to the diffuse baryon-photon fluid only through gravity. If this condition is not met – e.g. if the dark matter is supposed to be in the form of diffuse baryons up to recombination – it proves difficult to explain the smoothness of the CMB, on the one hand, and the highly structured local Universe on the other (Peebles 1993). A known counterexample to this statement is the baryon isocurvature model – see Peebles 1993 – which invokes isothermal primordial density fluctuations. Unfortunately there is no fundamental theory for the origin of isothermal fluctuations, and the results for adiabatic fluctuations are usually given concomitantly greater weight.

These considerations have led to widespread acceptance of the idea that the bulk of the dark matter is non-baryonic. However, as emphasised by the phrasing of the preceding paragraphs, neither case is watertight. Very possibly the Universe was not homogeneous at the time of nucleosynthesis – in particular inhomogeneities could be introduced during the quark-hadron phase transition (Applegate & Hogan 1985) – and in this case the upper limit on baryons relaxes to $\Omega_B \lesssim 0.3$ (Kurki-Suonio et al 1990). If we admit the possibility of isothermal fluctuations as the origin of present-day large-scale structure there is then no barrier, from cosmological considerations, to a purely baryonic universe. A baryonic universe might also be consistent with adiabatic fluctuations, but in this case we require the proto-clouds to have sufficiently high density that they decouple from the CMB well ahead of recombination.

5.2 Cloud formation

How might planetary-mass gas clouds form? The answer to this question depends on quite what mass needs to be explained. For clouds which lie at the upper end of the planetary range, a fairly straightforward answer can be given: they could form as the endpoint of hierarchical fragmentation of larger clouds undergoing collapse in the early Universe ($z \sim 100$). There is a substantial literature on the topic of hierarchical fragmentation, beginning with Hoyle's (1953) classic paper, mostly employing spherically symmetric gas clouds in free-fall, in which "fragment" masses are equated with the Jeans mass for the gas. In most calculations the hierarchy is assumed to terminate when the cloud becomes optically thick – at which point cooling is impeded – and there are sound reasons why this usually results in sub-stellar masses for the smallest fragments (Rees 1976). By the same token, however, the smallest fragments are limited to masses $M >$ a few $\times 10^{-3}$ $M_\odot$, so if the putative cold clouds are smaller than this then hierarchical fragmentation is not viable as a formation scenario.

There are some hints that the individual clouds may indeed have very small masses (§5.4), possibly as small as 10^{-5} $M_\odot$. Moreover the arguments given in the preceding section suggest that *the dark matter is not formed from baryons which were smoothly distributed at recombination, or even at nucleosynthesis.* The implication is that the proto-clouds formed in the *very* early Universe ($z > 10^9$, cf. Hogan 1978, 1993), and have maintained their identity right up to the present. (Two further indications that the clouds predate cosmic nucleosynthesis are the presence of metals in High Velocity Clouds, and the hints from quasar variability that the Universe might contain a critical density of planetary-mass objects — see §5.4 and §4.4.1, respectively.) We envisage that the proto-clouds formed during the quark-hadron phase transition (cf. Applegate & Hogan 1985), and are thus fossils of that era. Although this is clearly speculative, it is the most economical

hypothesis available.

5.3 Cloud stability

Supposing that we can find a sensible explanation for how the clouds might have formed, it remains to comprehend the observed/inferred properties of the clouds at the present time. A major part of this task is to understand the internal constitution of the clouds, and in particular their thermal balance (see also Gerhard & Silk 1996).

For equilibrium, the power radiated from each cloud must be balanced by some heat generated within. Unlike stars this heat is clearly not generated by nuclear fusion; there might plausibly be some exothermic chemical reactions occurring (e.g. $2\,\mathrm{H} + \mathrm{H_2} \rightarrow 2\,\mathrm{H_2}$), but the simplest hypothesis for Galactic clouds is that heat is deposited by energetic particles. In principle this could involve both photons and cosmic rays (their Galactic energy densities are similar); however, given that the clouds are transparent to optical photons (§4.3), but not to cosmic rays, it is likely that the cosmic rays dominate.

The local cosmic-ray heating rate for dense interstellar molecular gas is $\sim 3 \times 10^{-4}\,\mathrm{erg\,g^{-1}\,s^{-1}}$ (Cravens & Dalgarno 1978), and supposing the cloud temperature to be $T \sim 10$ K this immediately implies a thermal (Kelvin-Helmholtz) time-scale of order 10^5 yr. This is much greater than the sound-crossing time-scale ($\sim 10^2$ yr), so we see immediately that each cloud responds adiabatically to pressure perturbations and consequently dynamical stability is assured. Thermal stability is another matter.

Because the heating of each cloud is largely independent of its temperature, the radiative cooling must actually *decrease,* with increasing T, if it is to be thermally stable. If it were otherwise, the following scenario would take place. Suppose the cloud contracts slightly from an initial equilibrium condition, then its temperature increases, consequently it radiates more efficiently, but the heating rate remains the same, so cooling then outstrips heating and this causes further contraction. Evidently this contraction can continue without limit under the stated circumstances and such a cloud would be thermally unstable, collapsing (or expanding) on a thermal time-scale. As this is much less than the Hubble time, this is not an acceptable model. The difficulty we then face is that, in order to construct a thermally stable model, we need to identify a radiative cooling process which becomes *less* effective at higher temperatures.

While it is possible for this circumstance to arise, e.g. by virtue of a single spectral line becoming optically thick, it is a highly anomalous situation. In the particular case of the hypothesised cold, dense clouds there happens to be a remarkably simple solution to this conundrum (Wardle & Walker 1999). Conditions within the clouds are close to those required for the precipitation of solid hydrogen (Pfenniger & Combes 1994), and such particles efficiently cool the gas via their thermal continuum radiation. If this process dominates the radiative cooling of the clouds, then they can be thermally stable because an increase in temperature rapidly destroys the coolant, leading to less efficient cooling at higher temperatures. This concept is examined in detail by Wardle & Walker (1999).

5.4 Cloud survival

Beyond just the stability of the clouds, we need to understand their survival in the Galaxy for billions of years. This issue was first considered by Gerhard & Silk (1996), who arrived at simple criteria which the clouds must satisfy if they are not to be destroyed by evaporation or by collisions. Gerhard & Silk (1996) found the latter to be the more restrictive condition, implying a lower bound on the column density of individual clouds: $N \gtrsim 4 \times 10^{24}\,\mathrm{cm^{-2}}$. This constraint can be

tightened quite considerably by going beyond just order-of-magnitude estimates and examining the evolution, under the influence of collisions, of a model halo.

Starting from a singular isothermal sphere, Walker (1999b) found that the dark halo developed a core of constant density, with the core radius increasing as a function of time, as a result of destructive collisions between clouds. In this model the size of the core, r_c, is a function of the halo velocity dispersion, σ – large velocity dispersions imply high collision rates – with $r_c \propto \sigma^{3/2}$. There is some evidence that dark halos do indeed possess finite cores with the size of the core increasing as $\sigma^{3/2}$ (Kormendy 1990).

Collisions between clouds cause shock heating of their constituent material; these shocks typically dissociate the molecular gas and unbind the clouds, their material subsequently being assimilated into the ISM of their host galaxy. Walker & Wardle (1999) pointed out that the Galactic High Velocity Clouds (HVCs; Wakker & van Woerden 1997) might plausibly be identified with post-collision gas which has not yet been assimilated into the Galactic disk. If this identification is correct, the fact that HVCs contain metals is of particular interest because our naive expectation is that the composition of these clouds reflects the nucleosynthetic yields of the Big Bang. This is entirely unconventional, of course, but is in accord with the hypothesis that the clouds predate nucleosynthesis and introduce inhomogeneity at that epoch (§§5.1,5.2; Applegate & Hogan 1985).

In due course stars may form from the diffuse gas released by collisions, but either way the material is part of the visible pool of matter and consequently the visible mass within a dark halo can be predicted. Walker (1999b) discovered that data published by Broeils (1992) are in good agreement with this model; matching the theory to the data requires only that the surface density of individual clouds is $\Sigma \simeq 140\ \mathrm{g\,cm^{-2}}$ (assuming the age of the Universe to be 10 Gyr). Moreover it seems very likely that this relationship between visible galaxy mass and halo velocity dispersion, $M_{vis} \propto \sigma^{7/2}$, underlies the well-known Tully-Fisher relation between galaxy luminosity and velocity dispersion. This is a remarkable success for such a simplistic model, and this result assumes particular importance because it occurs in the arena where we find the strongest evidence for dark matter, i.e. the dynamics of spiral galaxies.

With the above estimate for the mean cloud surface density we can immediately compute the sky-covering fraction for the clouds: $f_{coll} \simeq 2 \times 10^{-4}$ (Walker 1999b). This is considerably smaller than the estimate based on ESEs ($f_{ESE} \sim 5 \times 10^{-3}$; Fiedler et al 1994), and if we wish to reconcile these values it seems necessary to contemplate photo-ionised winds arising at radii $(f_{ESE}/f_{coll})^{1/2} \sim 5$ times larger than the underlying hydrostatic clouds. Presumably, if both models are valid, this difference implies that a neutral wind transports mass out to several cloud radii before it becomes ionised. Thus since Walker & Wardle (1998a) estimate an inner radius of order 2 AU for the photo-ionised wind, we can estimate the underlying cloud radii as roughly 0.4 AU$= 6 \times 10^{12}$ cm. In combination with the estimated mean surface density, this implies that a characteristic mass for the individual clouds is $M \sim 10^{-5}\ \mathrm{M_\odot}$. (A cloud with this mass/radius ratio has a virial temperature of a few Kelvin, cf. §5.3.) As the line of reasoning which leads to this figure is not yet secure, the estimate should be treated with some caution.

A further interesting aspect of collisions is that the shock-heated gas radiates strongly, and this radiation may be detectable. In the case of collisions in the Galactic halo one expects (unobservable) extreme ultraviolet flashes, with accompanying optical transients at a median magnitude of $V < 23$, lasting a few days. For halos with larger velocity dispersions the thermal radiation moves into the X-ray band and is directly observable. Rather dramatically, the implied X-ray luminosity for a cluster of galaxies with $\sigma = 1000\ \mathrm{km\,s^{-1}}$ is (assuming polytropic clouds with n=3/2) $L_X \simeq 3 \times 10^{44}\ \mathrm{erg\,s^{-1}}$, comparable to what is actually observed from such clusters. Because this emission is thermal radiation from gas at roughly the virial temperature, it is difficult to distinguish it from thermal emission by *diffuse,* hot gas in the cluster (which is the standard

interpretation of the observed emission). These issues are discussed by Walker (1999c).

6 Observational tests

Having established that cold clouds could make up the dark matter, i.e. there is no evident inconsistency with observations, we can turn to the task of isolating some critical tests of the picture. Unlike the non-baryonic dark matter candidates, cold clouds interact with their environment in a rich variety of ways, admitting direct tests of the theory.

6.1 Lensing phenomena

A clear prediction of the model is that cosmologically distant sources should be strongly gravitationally lensed by intervening clouds. This possibility can be investigated relatively cleanly if one studies a large sample of quasars located behind low-redshift over-densities such as galaxy halos or clusters of galaxies (Walker 1999a; Walker & Ireland 1995; Tadros, Warren & Hewett 1998). In a collaborative effort led by Robert Smith (ANU), we are working towards this goal, making use of the large sample of objects identified in the 2dF Quasar Survey (Boyle et al 1996).

For clouds located in the Galactic halo, gravitational lensing is insignificant, but *gas* lensing may introduce measurable flux changes (Draine 1998). In the absence of a reliable structural model for the clouds there is great uncertainty in the predicted (de)magnification, making it difficult to use as a test. Nevertheless the requisite data have already been accumulated in the search for gravitational lensing events against LMC stars, and these data could usefully be searched for gas lensing events. Such a search should employ different criteria to those used to find gravitational microlensing (e.g. Alcock et al 1998): for gas lensing quite large differences in magnification can occur for different colours, and the light curves can be quite dissimilar to those for gravitational lensing by a compact object. We note also that the arguments presented in §5.4, suggesting a relatively small radius for the hydrostatic cloud, imply (high magnification) event time-scales of less than a day (cf. Draine 1998), and light-curves which are profoundly influenced by source size.

Plasma lensing (ESEs and related phenomena) is an area where further observational work would be extremely helpful. Pulsars offer the best targets for such work: they are much more informative than quasars in respect of the properties of the lens; multiple imaging is more common at low frequencies, where pulsars are brightest; and pulsars are very small in angular size, admitting sensitivity to distant lenses. Even rather basic information about the properties of the plasma lenses could discriminate between the various models. For example: if the lenses could be shown to be approximately axisymmetric and possessing an off-axis peak in electron column density, this evidence would very strongly favour the cold-cloud model. We also note that a 21 cm absorption line should arise during an ESE, but the strength of this line is difficult to predict because it depends on the tiny fraction of atomic hydrogen present within the cloud.

6.2 Extinction events

Throughout the far UV and X-ray bands the clouds must be completely opaque, implying that a small fraction of all compact extragalactic sources should be extinguished in these wavebands. However, these bands require space-based instrumentation and intensive monitoring experiments are consequently difficult to pursue. The best prospect for discovering clouds through their extinction therefore seems to be an accurate monitoring program at the blue end of the optical band, looking for Rayleigh scattering by the H_2. Modelling the cloud-cloud collision process (§5.4; Walker 1999b) provides an estimate of the mean cloud surface density $\Sigma \simeq 140\ \mathrm{g\,cm^{-2}}$, which

translates to a mean column density in H_2 of 3.1×10^{25} cm^{-2}. Using the scattering cross-section of Dalgarno & Williams (1965) this implies an average extinction of $\Delta B \simeq 0.073$ magnitudes, while $\Delta V \simeq 0.032$ and $\Delta R \simeq 0.012$. (Gas lensing [§§4.4.2, 6.1] also affects the received flux; however, for most of the time during a gas lensing event the received flux is lower than if the lens were absent, so that gas lensing typically reinforces the effects of extinction.) At shorter wavelengths, scattering quickly becomes a large effect: 0.25 mag at 336 nm, and 0.85 mag at 255 nm. Extinction events should last only a week or two, and should be manifest in a fraction $\simeq 2 \times 10^{-4}$ of Magellanic Cloud stars, say, at any one time.

6.3 Local Hα sources

By virtue of their small mass, the nearest dark clouds ought to be quite close to the sun – perhaps within 0.1 pc – and it may be possible to detect these objects through their Hα emission. In the solar neighbourhood the mean intensity of ionising photons appears to be very low (Vallerga & Welsh 1995) and will not lead to a detectable emission measure, even for a cloud which is so close that it is resolved by the telescope. However, the cosmic rays which pass through the cloud create some ionisation throughout its volume, and a small fraction of these ionisations lead to the production of Hα photons.

More specifically, cosmic-ray ionisation of He gives He^+ which reacts with H_2 to give He, H and H^+, the last of which recombines with an electron, yielding emergent Balmer photons. (By contrast, ionisation of H_2 leads to the formation of H_2^+, which reacts with H_2 to give H_3^+; this subsequently recombines with an electron to yield H_2 and H.) Assuming that roughly 60% of H^+ recombinations yield an Hα photon – as for Case B conditions – and adopting an ionisation rate of 3×10^{-17} s^{-1} (e.g. Webber 1998), the implied Hα luminosity is $2 \times 10^{35} M_{-4}$ s^{-1}, where M_{-4} is the cloud mass in units of 10^{-4}M$_\odot$. Now from the results of Walker (1999b) we can infer a local cloud density of $80/M_{-4}$ pc^{-3}, so if we survey a solid angle of ω sr, the brightest cloud within the survey area is expected to have a flux of $1.5 \times 10^{-2} M_{-4}^{1/3} \omega^{2/3}$ cm^{-2} s^{-1}.

By good fortune it happens that the Anglo-Australian Observatory has recently commissioned an Hα filter for use with its Schmidt telescope. In three hours this combination reaches a depth approximately equivalent to $R = 21$ (Parker 1998), and using the magnitude-flux transformation of Bessell (1983) we find that this corresponds to 2.0×10^{-4} cm^{-2} s^{-1}. In collaboration with Quentin Parker (ROE) and Mike Irwin (IoA), we are currently using this telescope/filter combination to search for local examples of the cold cloud population. The technique we are using is to observe eight high-latitude fields (total $\omega = 3.1 \times 10^{-2}$ sr), in both Hα and R to similar depth, then re-observing these fields one year later in order to identify any high proper-motion emission-line sources. Sciama (1999) has pointed out that the local cloud population should also be detectable with future satellite missions (MAP and Planck) designed to study the Cosmic Microwave Background. These missions are, however, some years away.

6.4 Collisions

The theory described in §5.4 implies that optical transients will arise from cloud-cloud collisions occurring within the halo of our Galaxy. We estimate that the median of the distribution of peak visual magnitudes will be $V < 23$; the total event rate will be roughly $0.7/M_{-4}$ deg^{-2} yr^{-1}; and typical durations will be a few days. The estimated magnitude assumes that the internal density profile is approximately that of a convective ($n = 3/2$) polytrope; more centrally concentrated profiles result in fainter (median) transients (e.g. fainter by 3.6 mag if $n = 3$). Although the properties of the transients are at present only crudely predicted by the theory, we know of no

similar physical phenomenon and it seems unlikely that, if discovered, the origin of such events would be incorrectly attributed. Discovery would require a fairly deep, wide-area monitoring program with daily visits and rapid spectroscopic follow-up. Because the radiating gas reaches temperatures of approximately 5×10^5 K, optical spectra will presumably display emission lines superimposed on a continuum dominated by free-free emission and He^{++} recombination.

A further implication of the physics described in §5.4 is that a large fraction of the X-ray emission observed from clusters of galaxies must be attributed to cloud-cloud collisions. If this is really the case, then it follows (Walker 1999c) that the X-ray satellite Chandra will resolve the nearby Virgo cluster into a large number of point-like, transient X-ray sources.

6.5 γ-ray background

A direct view of the bulk of the clouds is afforded by their γ-ray emission, and it would be helpful to study the spectral properties and angular distribution of the γ-ray background. Unfortunately there appears to be no immediate prospect for such studies. The Compton GRO satellite was able to detect the Galactic component of the high energy γ-ray background (Dixon et al 1998), but lacked the sensitivity necessary to conduct studies on angular scales much less than a radian. Future gamma-ray missions – notably NASA's GLAST satellite (http://glast.gsfc.nasa.gov) – will have much greater sensitivity than CGRO, but are currently some years away from realisation. In the meantime it would be profitable to calculate the spectrum which is expected from cosmic-ray interactions with clouds of high column density. This may be relevant to the existing EGRET data on diffuse emission, whose spectra are not understood (Mori 1997).

7 Theoretical outlook

In addition to observations designed to test the proposed picture, there is a need to develop the model more fully. The most blatant deficiency of the current picture is that the origin of the putative clouds is unspecified. As described in §5.2, there are some hints that the clouds formed in the very early Universe, prior to synthesis of the light elements, and this scenario could usefully be pursued theoretically. Unfortunately the physics appropriate to this era involves non-perturbative QCD and is currently unclear, so definitive investigations are not possible at present.

The physics relevant to the present day clouds is not subject to these difficulties, and theoretical models of their structure can be constructed. For the central, hydrostatic core it is especially important to determine the density profile; this profile affects the typical kinetic energy dissipated during collisions, as well as the gas- and gravitational-lensing properties of the clouds. Similarly, a better understanding of the structure of the photo-evaporated wind would improve the predictive power of radio-wave lensing calculations — a critical area at present, given that radio-wave lensing phenomena currently provide much of our information on the clouds' properties.

It would be very useful to acquire a better picture of how the clouds evolved, from some (assumed) initial conditions right up to the present day. While the correct initial conditions are unknown at present, because the origin of the clouds is murky, such evolutionary calculations would help to clarify which formation scenarios are plausible. The properties of the cloud population prior to the epoch of recombination are particularly interesting, because these can be related to the measurements of Cosmic Microwave Background anisotropies. If the clouds are sufficiently dense that they decouple from the CMB well before recombination, then the development of large-scale structure in the Universe will presumably be qualitatively similar to that of the Cold Dark Matter (CDM) model, as the clouds are expected to be dynamically cold at decoupling. Some of the theoretical "machinery" currently used with CDM – notably the numerical simulations of

structure formation – could then be usefully applied to the cold cloud picture. As described in §5.4, however, the effects of cloud-cloud collisions on the dark matter distribution function would have to be incorporated in any simulations.

8 Summary

Extreme scattering events reveal the presence of compact, high pressure regions of ionised gas in the Galaxy; these are best explained in terms of photo-ionisation of cold clouds, but these clouds must contribute substantially to the Galactic dark matter. This interpretation involves no incompatibility with other data and most of its challenges are theoretical — i.e. the need to understand the origin, structure and evolution of the clouds. Model predictions to date have been in remarkable accord with observation; in particular the Tully-Fisher relation for spiral galaxies emerges as a natural consequence of the model.

The most controversial arena for the cold cloud model at present is cosmology, where the view that most of the dark matter is non-baryonic is usually rather firmly held. Nevertheless one can sensibly contemplate a purely baryonic universe if the baryons are inhomogeneously distributed at nucleosynthesis, and these inhomogeneities may be identified with the proto-clouds themselves. Consistency with the observed large-scale CMB anisotropies then requires either isothermal primordial density fluctuations or, if the fluctuations are adiabatic, early decoupling of the clouds from the CMB.

The cold cloud model still requires a great deal of theoretical development and observational investigation; in particular we need a definitive observational test of the existence of the putative clouds.

Acknowledgements

The authors are indebted to many colleagues for the insights they have shared with us on the topics described herein. In particular we wish to thank: James Binney; Roger Blandford; Leo Blitz; Bruce Draine; Ron Ekers; Andy Fabian; Eric Feigelson; Ken Freeman; Gordon Garmire; Mike Hawkins; Peter Kalberla; Ulrich Mebold; Bohdan Paczyński; Daniel Pfenniger; Sterl Phinney; Barney Rickett; Dennis Sciama; Lister Staveley-Smith; and Ravi Subrahmanyan.

References

Alcock C. et al. 1997 ApJ 486, 697
Alcock C. et al. 1998 ApJL 499, L9
Applegate J.H. & Hogan C.J. 1985 Phys. Rev. D 31, 3037
Ashman K.M. 1992 PASP 104, 1109
Bessell M.S. 1983 PASP 95, 480
Binney J. & Tremaine S. 1987 "Galactic Dynamics" (Princeton univ. Press: Princeton)
Bland-Hawthorn J. & Maloney P.R. 1997 PASA 14, 59
Bloemen H. 1989 ARAA 27, 469
Boyle B.J., Smith R.J., Shanks T., Croom S.M. & Miller L. 1998 proc. IAU Symp. 183, Cosmological parameters and the evolution of the Universe
Broeils A. 1992 "Dark and visible matter in spiral galaxies" PhD Thesis (Groningen)
Carr B. 1994 ARAA 32, 531

Clegg A.W., Chernoff D.F. & Cordes J.M. 1988 in Radio Wave Scattering in the Interstellar Medium, ed. J.M. Cordes, B.J. Rickett & D.C. Backer (AIP: New York) 174
Combes F. & Pfenniger D. 1997 A&A 327, 453
Cravens T.E. & Dalgarno A. 1978 ApJ 219, 750
Dalgarno A. & Williams D.A. 1965 Proc. Phys. Soc. Lond. 85, 685
Davis M., Efstathiou G.P., Frenk C.S. & White S.D.M. 1985 ApJ 292, 371
de Paolis F., Ingrosso G., Jetzer Ph. & Roncadelli M. 1995 Phys. Rev. Lett. 74, 14
Dixon D.D. et al 1998 New Ast. 3, 539
Dove J.B. & Shull J.M. 1994 ApJ 430, 222
Draine B.T. 1998 ApJL 509, L41
Dyson J.E 1968 Ap&SS 1, 388
Fiedler R.L., Dennison B., Johnston K.J. & Hewish A. 1987 Nat 326, 675
Fiedler R.L., Johnston K.J., Waltman E.B. & Simon R.S. 1994 ApJ 430, 581
Fixsen D.J. et al 1994 ApJ 420, 457
Gerhard O. & Silk J. 1996 ApJ 472, 34
Hawkins M.R.S. 1993 Nat 366, 242
Hawkins M.R.S. 1996 MNRAS 278, 787
Henriksen R.N. & Widrow L.M. 1995 ApJ 441, 70
Hogan C. 1978 MNRAS 185, 889
Hogan C.J. 1993 ApJL 415, L63
Hoyle F. 1953 ApJ 118, 513
Kormendy J. 1990 "Evolution of the universe of galaxies" ed. R. G. Kron ASP Conf. Ser. 10, 33
Kurki-Suonio H., Matzner R.A., Olive K.A. & Schramm D.N. 1990 ApJ 353, 406
Lagache G., Abergel A., Boulanger F. & Puget J.-L. 1998 A&A 333, 709
Mori M. 1997 ApJ 478, 225
Paczyński B. 1986 ApJ 304, 1
Palla F., Salpeter E.E. & Stahler S.W. 1983 ApJ 271, 632
Parker Q. 1998 Personal Communication
Peebles P.J.E. 1993 "Principles of physical cosmology" (Princeton Univ. Press: Princeton)
Pfenniger D., Combes F. & Martinet L. 1994 A&A 285, 79 (PCM94)
Pfenniger D. & Combes F. 1994 A&A 285, 94
Press W.H. & Gunn J.E. 1973 ApJ 185, 397
Reach W.T. et al 1995 ApJ 451, 188
Rees M.J. 1976 MNRAS 176, 483
Reynolds R.J. 1992 ApJ 392, L35
Rickett B.J. 1990 ARAA 28, 561
Romani R., Blandford R. D. & Cordes J. M. 1987 Nat 328, 324
Sahu K. 1994 Nat 370, 275
Schild R.E. 1996 ApJ 464, 125
Sciama D.W. 1999 MNRAS (Submitted: astro-ph/9906159)
Schramm D.N. & Turner M.S. 1998 Rev. Mod. Phys. 70, 303
Smoot G.F. et al 1992 ApJL 396, L1
Spooner N.J.C. 1997 Proceedings of the First International Workshop on Identification of Dark Matter (World Scientific: Singapore)
Tadros H., Warren S. & Hewett P. 1998 New Ast. Rev. 42, 115
Trimble V. 1987 ARAA 25, 425
Vallerga J.V. & Welsh B.Y. 1995 ApJ 444, 702
van den Bergh S. 1999 PASP (In press; astro-ph/9904251)

Wakker B. & van Woerden H. 1997 ARAA 35, 217
Walker M.A. 1999a MNRAS (In Press; astro-ph/9806196)
Walker M.A. 1999b MNRAS (In Press; astro-ph/9807236)
Walker M.A. 1999c ApJL (Submitted; astro-ph/9908103)
Walker M.A. & Ireland P.M. 1995 MNRAS 275, L41
Walker M. & Wardle M. 1998a ApJL 498, L125
Walker M. & Wardle M. 1999 "Proc. Stromlo Workshop on High Velocity Clouds" (eds. B.K. Gibson & M.E. Putman) ASP Conf. Ser. 166, p269
Wardle M. & Walker M. 1999 ApJL (Submitted: astro-ph/9907023)
Webber W.R. 1998 ApJ 506, 329
Webber W.R., Lee M.A. & Gupta M. 1992 ApJ 390, 96
Zwicky F. 1933 Helv. Phys. Acta 6, 110