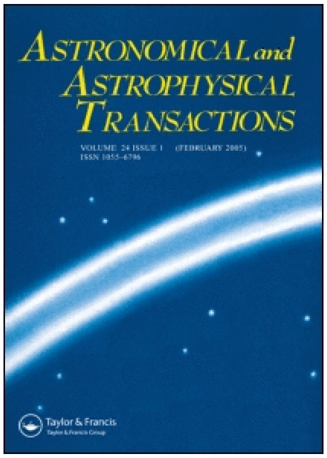

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DARK MATTER: FROM GALACTIC HALO TO SUPERCLUSTERS

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One topic relates to the possibility that the spherical dark matter halo of a spiral galaxy may contain neutron stars, brown dwarfs and asteroids. A possible connection between the "rotation curve conspiracy", super-globular-clusters and gamma-ray-bursts is discussed. The relationship between very large "Zeldovich pancakes" and the value of the Hubble constant is also discussed.

KEY WORDS Dark matter, gamma ray bursts, rotation curve conspiracy.

I. INTRODUCTION

I am honored to be able to help celebrate the memory of Yakov B. Zeldovich. The word "celebrate" is more appropriate here than "mourn", because the exuberance and enthusiasm of his personality carries over into memory. I met Yakov only relatively recently, at the IAU Assembly in Prague in 1967, and have considered him a true friend over these past 25 years. However, he has been a role model and inspiration for me from a much earlier period on: When I switched from the "pure" subject of quantum electro-dynamics to the "applied and messy" field of astrophysics, I sometimes felt the need of reassurance for such a switch. Zeldovich not only made several switches very successfully, but he demonstrated brilliantly how to use experience from a pure field in more applied work. He was also a role model in another "applied and messy" field which is not usually mentioned at scientific meetings, namely work for the military establishment: I worked on the reentry physics of ballistic missiles for one side of the cold war—only a little, but enough to become impressed by the brilliant work he had done for the other side. These are difficult times in some ways, but being able to reminisce about the cold war is itself reassuring.

The halo of an individual spiral galaxy is probably the smallest scale where we have firm evidence for dark matter, the superclusters which contain many Abell-type galaxy clusters (a better word would be super-supercluster) the largest. There are interesting structures on intermediate scales, such as galaxy pairs where we now have data for pairs at quite large separations (~1 Mpc) and fairly small velocity differences (Zaritsky *et al.*, 1993; Chengalur 1993). Masses to be associated with them are still quite uncertain, but these pairs illustrate a general principle: Although morphologically distinct structures such as "galaxy", "pair", "local group" and "cluster" are thought to have quite different characteristic sizes, there is a lot of overlap. We think of "typical" pairs with ~100 kpc separation, but Chengalur's pairs are larger than the cores of some classical clusters. I will not discuss these pairs any further in this short contribution, but will mention another intermediate structure later, namely a "cloud of local groups" (Sect. IV).

I shall concentrate here on just two topics from the two ends of the distance scale. One is the question of whether galaxy halos could consist mainly of baryonic dark matter in general and, specifically, of neutron stars. The juxtaposition of compact objects with large scale structure is itself reminiscent of Yakob's breadth of vision. My other topic is the effect on Hubble constant measurements of "super-superclusters", the most spectacular examples of "Zeldovich pancakes" (Zeldovich 1970).

II. THE ROTATION CURVE CONSPIRACY, HOLLOW HALOS AND SUPER-GLOBULAR-CLUSTERS

Consider first the possibility that the bulk of the dark matter halo of a spiral galaxy is *not* baryonic, but is a distribution (cold or hot) of some kind of fundamental particles. The baryonic inner component of the proto-galaxy, which eventually forms the visible stellar population, will have been affected by the gravitational pull of the more massive halo in a general way. But in a more specific way the physics is different, so the history must have been different and the mass distributions of the visible and dark matter components are likely not be related in any detailed manner. If one takes this point of view of two independent distributions, then some simple observational results on galaxy rotation curves become puzzling, if not "a conspiracy" (Bahcall and Casertano 1985; see also Sancisi and van Albada 1987): The visible component dominates gravity at small radial distances r, the dark matter at larger r; if the two distributions are unrelated, one should expect some complex behavior of the rotation velocity $V_{\mathrm{rot}}(r)$. Instead, one observes (averaging over small-scale irregularities) a smooth rotation curve from the rising portion at small r to the almost constant $V_{\max}$ at larger r. The constant $V_{\max}$ plus Kepler's laws shows that the dark matter mass $M_{DM}(r)$ increases linearly with r. The numerical value of $V_{\max}$ is determined by a purely dark matter property, $M_{DM}(r)/r$, but observationally the "Tully-Fisher law" (see, e.g. the review by Jacoby *et al.*, 1992) notes a tight correlation between $V_{\max}$ and the galaxy luminosity L, obviously a visible matter property.

This "conspiracy" would not be present if there were not two independent mass distributions, but only a single component present in the proto-galaxy. Since the visible matter consists of baryons, the dark matter in a galaxy halo also has to be baryonic on this hypothesis. This still leaves open the possibility that the distributed dark matter in galaxy clusters is made up of some non-baryonic fundamental particles. Even in a galaxy halo the baryonic dark matter needs to extend out only as far as we have observational data on rotation curves, i.e. three or four times further out (~40 kpc for a galaxy like ours) than where the star density is large. In terms of the dimensionless cosmological density parameter Ω, the minimum baryonic component for the hypothesis is only about $\Omega_b \gtrsim 0.03$, compatible with nucleosynthesis in the early universe. There could also be additional non-baryonic dark matter distributed throughout our Local Group, for instance, as long as it does not dominate in the inner 40 kpc of Andromeda and the Milky Way. The next question is what form the "invisible" baryonic matter takes inside this region.

We have upper limits on the amount of gas in galactic halos and that is negligibly small compared with the required dark mass. In the mass range of condensed objects from rocks to black holes, one class must be strongly underrepresented to give a dark halo, namely long-lived main sequence stars. Fortunately, the concept of "bimodal star formation" [Herbig (1962); Larson (1986); Shu, Adams and Lizano (1987); Wyse and Silk (1987)] provides a plausible scenario—or at least enough uncertainty for a possible one: Crudely speaking, "bimodal star formation" implies that the standard initial mass function (IMF) for population I stars is the average of two other distributions, one concentrated toward massive stars born in "violent" regions, the other towards low mass stars born in "quiescent" regions. This picture has the possibility of an extreme instability in it—e.g. under some circumstances a slight preference for massive stars might produce so many supernovae as to keep the interstellar gas so "violent" that the IMF is tilted even further towards massive stars, etc. In particular, the question arises whether conditions were sufficiently different when the galaxy was young to have favored a "massive IMF" and violence or a "low mass IMF" and quiescence. Baade (1944) enunciated the concept of "stellar populations I and II" (see review by Sandage 1986) and the stellar population II is certainly the older and inhabits the nearby portion of the halo. There is no compelling observational reason to believe in a radically different IMF for population II, compared to the present-day IMF. If one extends Baade's concept only backwards in time, but *not outwards* in space, "stellar population III" would merely mean "the earliest of population II" with continuity between them. There is some suggestion that massive stars led to supernovae and to some metal enrichment early in this continuity [Spite and Spite (1985); Cayrel (1986)], but there would not be room for a very drastically different IMF. However, we are dealing with the concept of a baryonic dark matter halo which mostly lives at *larger* radial distances r from the galactic center than ordinary globular clusters and population II. This spatial separation allows greater freedom in making models, both for the IMF and for the nature of a "hollow halo".

The simplest model that is usually invoked for the present-day dark matter density distribution is

$$\rho_{DM}(r) = \text{const} \times [r^2 + a^2]^{-1}, \tag{1}$$

where a is a constant. However, to resolve the "rotation curve conspiracy" it is more natural to assign a smooth distribution as in Eq. (1) to the total initial protogalactic gas distribution. One then has to invent some scenario which preferentially turns the initial baryon gas into visible stars in the inner region (disk and globular cluster halo) and into dark objects in the outer regions. With the visible matter occupying a central core, the dark matter halo must be "hollow" at least to some extent, i.e. inside some core radius R_c the present day $\rho_{DM}(r)$ must be smaller than Eq. (1). Theoretically, the degree of the "hollowness" today depends on the details of the division into the two components and on the type of orbits: for the two unlikely extremes the result is clearcut, i.e. for circular dissipationless orbits the hollowness is preserved, for purely radial orbits it is wiped out. Observationally, considerations of the "Oort limit" should tell us about dark matter in our vicinity which is likely to be inside the core radius R_c. However, uncertainties are still large enough to be compatible with the most likely intermediate situation-some ρ_{DM} for $r < R_c$ but less than in Eq. (1).

With most of the dark objects spatially separated from the inner galaxy, one can postulate an extreme form of the IMF for this "outer halo stellar population III", invoking low metal abundance, low magnetic fields, low density, etc. for the extremeness. The IMF could favor low masses, even rocks or asteroids but more likely brown dwarfs (see, e.g. Adams and Walker 1990; Lenzuni, Chernoff and Salpeter 1992; Salpeter 1992) or it could favor forming massive stars which have all resulted in neutron stars and black holes by now. In the latter case an enormous amount of heavy elements will have been produced by supernovae at early times and one needs a model which prevents the metal-rich supernova debris from contaminating the gas from which the earlier stellar population II stars formed. Because of the "hollowness" there is less spatial overlap, but there is still enough overlap for this to be a problem. Probably the easiest way to minimize this problem is to postulate that the massive stars in the outer halo were not formed singly or in small groups, but inside of very massive proto-clusters [Cayrel (1986); Carr and Lacey (1987); Wasserman and Salpeter (1992)]. In such a model only the debris from supernova blast waves originating near the cluster surface escape into the general interstellar medium. To minimize the resultant contamination one wants to have the mass M_{cl} per cluster as large as possible. Massive clusters would heat up the stellar galactic disk (Carr and Lacey 1987). If one attributes the present disk thickness all to this effect (and estimates the degree of hollowness), one requires $M_{\mathrm{cl}} \sim 10^7 M_\odot$, i.e. one is dealing with 'super-globular-clusters' (Wasserman and Salpeter 1992). This mass estimate also holds if brown dwarfs form instead of massive stars.

The postulate of super-globular-clusters also leads to at least one model of how to achieve visible/dark separation. Assume the size of a gaseous proto-cluster is independent of its location, so the number density of these objects was given by Eq. (1). The rate of head-on collisions between two such gas spheres was then larger in the inner halo than further out and the gas got distributed after such a collision. One then only needs to postulate that only the gas in an intact proto-cluster forms stars with very low or large mass, whereas distributed gas after a collision leads to the standard IMF. On such a picture, the proto-super-globular-clusters were the first objects to form in a spiral galaxy and most (but not all) of them eventually produced the dark population III stars. In that sense the nomenclature III, II, I for early, medium, late is logical. However, the chronology of the instances of actual star formation could be more complicated. Star formation (III) in an undistributed proto-cluster may continue for a considerable time period, as long as this period is short compared with the Hubble time. Stellar population II, on the other hand, is presumably formed by a variant of the suggestion by Eggen *et al.* (1962): Those protoclusters, which happen to have very small angular momentum, i.e. are on a plunging radial orbit when they first formed, will get to small radial distances in a single free-fall time, suffer collisions and dissipation. In this manner population II stars may have formed quite rapidly. On the other hand, the onset of population I is delayed somewhat since two proto-clusters with angular momentum have to collide first before dissipation starts.

III. THE MACHO PROJECT AND GAMMA RAY BURSTS

The models proposed in the last section are of course "double farfetched", i.e. they invoke an unusual stellar IMF and then postulate clusters in the outer halo about 100 times more massive than an ordinary globular cluster. It is therefore important to have some observational predictions which can be tested eventually. Fortunately, the super-globular-clusters are fairly well constrained to $M_{cl} \sim 10^7 M_\odot$, as mentioned above, and radius (estimated from collision requirements; see Wasserman and Salpeter 1992) of $R_{cl} \sim 30 pc$ and internal velocity dispersion $V_{cl} \sim 50\,\mathrm{km\,s^{-1}}$, slightly smaller than the typical cluster orbital velocity. The angular size of a typical cluster (say, 10 to 20 kpc away) is a few times smaller than the typical spacing on the sky of $\sim 1°$. The MACHO project (Alcock *et al.*, 1992) is an ideal observing strategy for the low mass model, i.e. if the dark objects have masses like Jupiter or brown dwarfs (10^{-3} to $0.1\,M_\odot$): The gravitational microlensing is done by an individual object out of $\sim 10^8$ per cluster and there should by several, but not an enormous number, of clusters in front of the Magellanic Clouds. If such objects are indeed detected at all, the statistics should soon accumulate to check for the clustering.

If the dark objects in the outer halo are mostly neutron stars, it is likely that *some* gamma ray bursts (GRB) are produced, even if it should turn out that *most* GRB are quite some different phenomenon at cosmological distances (see Paczynski 1992). Since one postulates so much more mass in neutron stars than in ordinary stars, packed into fairly compact clusters, some kind of violent activity seems likely. Wasserman and I favor a model where the IMF inside a proto-cluster switches fairly abruptly from favoring high mass (giving neutron stars) to low masses including "asteroid-like" masses $\sim 10^{24}$ g. Asteroids falling into neutron stars then provide one kind of GRB, but we also predict spatial correlation with enhanced optical (near infrared) surface brightness: With the IMF favoring both high and low masses, there must be some intermediate mass visible stars (0.1 to $1\,M_\odot$) in each cluster as well, giving optical emission within a fraction of a degree of a GRB (see also Silk 1992).

The BATSE detectors aboard Compton Observatory (Meegan 1992) observe many faint GRB. The absence of a concentration to the galactic plane has already ruled out an origin inside the galactic disk. The BATSE upper limit to the galactic dipole moment has also ruled out a monotonic source distribution as in Eq. (1) with a ~ 10 kpc (as required by the galaxy rotation curve). With the "hollow halo" distribution discussed above, the BATSE dipole moment alone is not a sufficiently stringent discriminant: Consider the hypothetical case of a completely hollow halo, i.e. $\rho_{DM} = 0$ for $r < R_c$ and Eq. (1) for $r > R_c$, and R_c slightly larger than out radial distance $R_0 \sim 8.5$ kpc. The nearest sources would then be at the core boundary in the *anti*-center direction and one might almost expect a *negative* dipole moment; at any rate a smaller positive dipole moment than Eq. (1) without a hole would give. However, the detailed angular distribution predicted for a hollow halo would *not* be isotropic, since the galactic center and anti-center directions are singled out. The BATSE data to date may already rule out that *all* GRB are of this type but, conversely, if some fraction are, the BATSE angular distribution should be affected. I have discussed here only models for halo neutron stars where these constitute the bulk of the dark matter in a galactic halo. If the dark matter is mostly non-baryonic, one can still have a *smaller* contribution from neutron stars which are in an outer halo but with $r \gg a$ [see, e.g. Duncan and Thompson (1992); Hartmann (1992)]. Such models have more flexibility on predicting the angular distribution, but are more likely to predict some enhancement of sources in directions towards the Magellanic Clouds and/or Andromeda. Thus, for any model except a strictly cosmological one, the GRB angular distribution will be of interest.

IV. SUPER-SUPERCLUSTERS, Ω AND H_0

So far we have only scant evidence from high redshift observations (Uson and Bagri 1991) for the process of forming a "Zeldovich pancake", (Zeldovich 1970) i.e. generating a sheet-like singularity. However, we have very strong present-day evidence for the aftermath of such a process on a very large scale, namely the sheet-like superclusters containing several (or even many) Abell clusters of galaxies. Historically, the earliest observations on a sheet-like collection of galaxies was on the Virgo Supercluster (or Local Supercluster) even though it contains only one galaxy cluster, the classical Virgo cluster (de Vaucouleurs 1961). The more recent galaxy surveys have shown up these much larger "sheets" (or super-superclusters) containing Abell clusters and loose groups between the clusters. One of these is the so called "Great Wall", behind the Virgo cluster and about six times as far (Ramella, Geller and Huchra 1992). These coherent large regions of overdensity in the galaxy distribution are impressive and gravitationally important, but so are the large underdense regions, the "Voids" between the overdense sheets. The relation of these two kinds of structures is clear qualitatively—material from the Voids streamed in to form the sheets—but controversial quantitatively, because of "biasing":

The gravitational growth of clustering which culminates in the "pancakes" mainly involves the dark matter which contains most of the mass, but we observe and count only the visible galaxies. Especially if the dark matter is non-baryonic, there can be some segregation between dark matter and the baryonic proto-galaxies and the mass to light ratio M/L may vary even for the baryonic component. We have reliable values for the mass to light ratio only for the dense virialized cluster cores and the concept of "biasing" suggests that this ratio is larger in the lower density regions. In terms of the dimensionless cosmological density parameter this uncertainty is heightened by the fact that we have to deal with two kinds of "non-cluster" regions, the spectacular Voids with few galaxies and the less spectacular intermediate density regions with more galaxies in total then in the clusters. Our neighborhood is typical of the intermediate regions and it contains loose unbound "clouds" of bound groups, including our own Local Group. The two specific questions affecting Ω are then (i) how much larger (if any) is M/L in a "cloud of local groups" than in a cluster and (ii) how much dark mass (if any) is there in Void regions where there are essentially no visible galaxies?

The sheets and the Voids between them not only have a direct effect on Ω, but also an indirect one on the measurement of the Hubble constant H_0 (Jacoby *et al.*, 1992; Pierce and Tully 1988). Observations on a pair of galaxies gives a "Hubble ratio" between the velocity difference and the distance, but this equals

H_0 only if there are no velocity deviations from Hubble flow. The slowing down of Hubble expansion inside our "local cloud of local groups" is important when nearby galaxies are used (Tully 1988). When widely separated galaxies behind Virgo and in the opposite direction are used (Lu *et al.*, 1993), the largest structures are important (Turner *et al.*, 1992). It is easy to observe where the densest Zeldovich pancakes are located (such as the "Great Wall"), but what matters most here is what the excess mass is when sheets and voids are considered together. For instance, a prominent pancake might signify a particularly extreme evacuation of the surrounding voids rather than an overall mass excess. Solving this problem will require a particularly delicate combination of cosmology, fluctuation theory and hydrodynamics—we will miss Yakov Zeldovich particularly severely here!

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