Supermassive Black Holes and Galaxy Formation

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ABSTRACT

The formation of supermassive black holes (SMBH) is intimately related to galaxy formation, although precisely how remains a mystery. I speculate that formation of, and feedback from, SMBH may alleviate problems that have arisen in our understanding of the cores of dark halos of galaxies.

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1. INTRODUCTION

Galaxy formation theory is not in a very satisfactory state. This stems ultimately from our lack of any fundamental understanding of star formation. There is no robust theory for the detailed properties of galaxies. In contrast, the hierarchical formation of large-scale structure in a cold dark matter-dominated Friedmann-Lemaître universe has successfully confronted essentially all observations, ranging from deep surveys of the galaxy distribution, the formation of galaxy clusters, and the temperature fluctuations in the cosmic microwave background.

2. The apparent demise of CDM

The advent of high resolution N-body simulations has revealed challenges for galaxy formation. Dark halos contain considerable sub-structure, amounting to of order 10% of the halo mass, and continuing down to unresolved scales of $10^9 M_\odot$ or smaller. This has led to two problems. One is that the predicted number of dwarf galaxy satellites exceeds that observed around the Milky Way by an order of magnitude. Even very low surface brightness dwarfs are easily observed in our local environment, and efficient mass loss prior to star formation has been invoked to resolve this discrepancy (Gnedin 2001).

However, since stars will form before the gas is entirely stripped, the dwarfs should be visible. Star formation is a local process that occurs in localized inhomogeneities, and the local free-fall time is short because the sound crossing time is short, whereas stripping is a global process that requires star formation to first occur, even if externally imposed, e.g. by an ionizing UV radiation field.

Another manifestation of excessive substructure in CDM halos is the failure of the CDM model to account for the velocity dispersion distribution of low ionization damped Lyman alpha systems at $z > 1.5$ (Prochaska and Wolfe 2001). The kinematics reveal too few clouds with velocity widths of 100 km/s or more compared to the number of low velocity width systems. It is unlikely that feedback plays much of a role in these systems, selected by absorption in low ionization, neutral gas, and with velocity widths that are unlikely to be affected by photoionization.

A second problem is that while the initial angular momentum of a typical protogalaxy when the halo first collapsed can reproduce the observed size distribution of disks if angular momentum is approximately conserved during baryon infall and disk accretion, the numerical simulations show that most of the angular momentum is actually lost to the dark halo. The clumpiness induces strong angular momentum transfer via tidal torquing and dynamical friction from the dissipating baryons to the energy-conserving dark matter. The resulting disks have too little specific angular momentum by an order of magnitude (e.g., Navarro and Steinmetz 2000a; Eke, Navarro and Steinmetz 2001). It seems likely that stellar feedback can in principle provide sufficient input of momentum to the infalling baryons via supernova explosions and remnant formation to avoid much of the angular momentum loss, at the price however of a significant delay in disk formation. Giant disks, in particular, would form relatively late, in possible conflict both with the observational evidence at $z \sim 1$ (Faber et al. 2001) and with ages in the outer parts of nearby disks (Ferguson and Johnson 2001). A more serious concern for those theoretically inclined is that there is as yet no robust prescription for the required feedback, although progress is being made (Couchman and Thacker 2001).

Another result from the high resolution simulations of galaxy halos is that the dark halo has a central concentration and a central cusp. The halo profile is described by a universal profile

$$\rho = \frac{A}{r^\gamma (r + r_s)^{3 - \gamma}},$$

where $A$ and $r_s$ depend on the cosmological model parameters and normalization, and $1 < \gamma < 1.5$. The CDM concentration parameter, defined as $C = r_s/r_v$, where $r_s$ is the scale radius where the density profile flattens and defines a cusp or core, and $r_v$ is the virial radius, is predicted to be 10-20 by numerical simulations. This implies for example that about half the mass within the half-light radius (for our galaxy this corresponds to near the solar circle) is in the form of CDM (e.g. Navarro and Steinmetz 2000b; Eke, Navarro and Steinmetz 2001). This apparently contradicts bulge microlensing studies for the Milky Way, which permit a CDM fraction of at most 10% within the solar circle, when combined with the rotation curve and infrared (DIRBE) stellar population modelling (Binney and Evans 2001). The status of the dark matter content of the inner Milky Way is uncertain by about a factor of 2 due to the uncertainty in the optical depth to microlensing. Dynam-
ical studies of nearby barred galaxies conclude that self-gravity of the bars, which consist primarily of stars, must dominate the inner gravitational potential (Sellwood and Kostosky 2000). At most, a 10% contribution by spherically or axially-symmetrically distributed dark matter can be allowed within the bar region to avoid conflict with the observed kinematics of certain barred galaxies. Both the bars and the matter within the inner galaxy out to a bar radius are required to be baryon-dominated by the need for gravitational instability to explain the existence of bars.

In contrast, a recent study of a non-barred spiral finds that detailed modelling of the rotation curve with a maximal disk requires an axially symmetric dark matter contribution of about 30% within an optical radius (Kranz, Slyz and Rix 2001). This is not inconsistent with bar formation by secular instability of a cold disk, but raises the question of why there is an apparently large spread in dark matter content among disk galaxies.

The pioneering study by Navarro, Frenk and White (1997) found a cusp profile of γ ≈ 1, but this has been superceded by higher resolution simulations which almost invariably find that γ ≈ 1.5 for galaxy mass halos (Moore et al. 1999; Jing and Suto 2000; Klypin et al. 2001).

There is another observational hurdle to overcome. Low surface brightness spirals are everywhere dark matter-dominated, and so provide outstanding laboratories for dark matter studies via rotation curves. High resolution Hα rotation curves reveal a wide array of central profiles. Most systems have soft cores without any indication of a central cusp, but some do show indications of γ being as large as unity. None however approach the predicted value of 1.5, and the best studied examples are in clear conflict with such a steep cusp (van den Bosch and Swaters 2001).

3. Resurrection of CDM

Cold dark matter is seriously challenged. Whether it is actually dead is quite another matter. Nevertheless, to confront this possibility, there have been numerous attempts to resurrect CDM. These come under two distinct guises: tinkering with the particle physics or elaborating on the astrophysics.

Particle physics variations include the introduction of self-interacting dark matter. Self-interactions, via elastic scattering, allow the dark matter to develop a smooth core. If the scattering mean free path is adjusted to be of the order of the core size, one can avoid developing an excessive central concentration of dark matter. This comes at a price, however: for example, the dark halo is found to be spherical, in apparent contrast to the elongated shapes inferred via gravitational lensing of dominant massive cluster galaxy halos (Miralda-Escude 2000).

Warm dark matter has provided a possible resolution of the cold dark matter “crisis”. A sterile neutrino with a mass of around 1 keV can constitute the dark matter, since its sterility enables the neutrino abundance to be suppressed relative to the ordinary neutrinos, and thereby avoid the hot dark matter mass bound for overclosing the universe. At 1 keV, the free-streaming length is of order the comoving scale of a dwarf galaxy. Substructure is suppressed. However high resolution simulations find that warm dark matter still produces a central cusp, although with γ ≈ 1 (Bode et al. 2001; Knebe et al. 2001). Possibly more serious is another consequence of the suppression of small-scale structure, which results in late formation of dwarf galaxies. If nearby dwarfs contain genuinely old stellar populations, this would be difficult to understand in the context of warm dark matter. Perhaps more serious maybe the need for a substantial spatial density of ultraluminous quasars at $z > 6$, each requiring a central SMBH of mass somewhat in excess of $10^{9} M_{\odot}$ (Fan et al. 2001). The diminished power of WDM makes it difficult to reconcile observations of this type with WDM. The abundance of massive ($\sim 10^{12} M_{\odot}$) halos is unaffected, but these form late: it is necessary to have small-scale power at high redshift to form the dense cores within which the SMBH formed.

More complex versions of particle dark matter have been proposed. These include self-interacting warm dark matter, a model which inspires little confidence given the difficulties encountered by warm and interacting dark matter, and more exotic variants such as shadow dark matter. Modified particle dark matter can no doubt be developed to explain all of the required dark matter properties. However the seductive simplicity of the SUSY LSP as an attractive candidate for CDM is lost.

An alternative approach is via the astrophysics of galaxy formation. Can the dark matter profile be modified by astrophysical processes? The answer is perhaps. Consider the following sequence of events. Supermassive black holes form at the cen-
tress of dark halos, possibly contemporaneously with, and certainly coupled to, the formation of the stellar spheroid. This sequence of events is strongly motivated by the observed correlation between supermassive black hole mass and spheroid mass (Ferrarese et al. 2000; Gebhardt et al. 2000) as well as by the super-solar abundances found in quasar broad emission line regions (Hamann et al. 2001).

Now consider a merger between a dwarf spheroid, containing a massive black hole, and a much larger galaxy. The smaller massive black hole spirals in under dynamical friction and eventually merges with the SMBH of the dominant galaxy. The details of the merger are not clear, but it seems likely that the smaller SMBH decays into tighter and tighter orbits as stars are ejected into the regime where gravitational radiation eventually takes over. Gas is essential for the initial formation of the SMBH, but dark matter cores and stars are crucial for the SMBH to undergo merger-induced growth. The process is well matched to galaxy formation. The dwarf galaxy stars are stripped and help feed and regulate spheroid growth.

However there is feedback on the dark matter. The SMBH merger results in heating of the dark matter cusp. The region that undergoes heating can be quite extensive as a transient rapidly rotating gaseous bar forms during the merger, and is slowed by dynamical friction. The dark matter is heated and acquires angular momentum. The result is that the concentration and cusp are likely to be modified. Simulations suggest that the inner profile flattens to $\gamma \approx 0.5$ (Nakano and Makino 1999; Merritt, Cruz and Milosavljevic 2001) This is considerably flatter than the initial cusp, and is insensitive to the initial density profile. The substructure is unaffected. However the angular momentum acquired by the halo will help in reinjecting angular momentum into infalling gas clouds that form the disk over a time-scale of a gigayear or longer.

A more dramatic interaction of the black hole with the dark matter may be imagined. Suppose there is an early accretion phase onto the SMBH, perhaps driven by transient bar formation. The activated SMBH will produce a vigorous outflow. The inner region is baryon-dominated. If enough baryonic mass loss occurs, the inner dark matter profile will be less concentrated and more uniform (Binney, Gerhard and Silk 2001). The modifications occur within the region where the baryon content changes from being dominant to being sub-dominant, i.e. of order half of the baryonic mass must be driven out, possibly just into the halo.

LSB dwarfs may be extreme examples where such mass loss has occurred. It is precisely these objects that provide possible evidence for ‘discrepant’ CDM profiles. Even in the absence of strong outflows, important dynamical heating can occur via dynamical friction on the rotating bar. Hence LSB galaxies, galaxies which had primeval bars (and so may be vulnerable to formation of a second bar if there is a suitable supply of gas), and galaxies with soft stellar cores, where SMBH mergers may have initiated stellar ejection, are the prime examples where the initial CDM profile is likely to have been modified.

Evidently, there is no firm prediction about dark matter profiles, whether in LSB galaxies or in luminous galaxies. I turn now to observations of dark matter, and discuss whether one can indeed observe the inner profile of dark halos.

4. "Observing" dark matter

The favoured candidate for CDM is the lightest stable SUSY relic particle. This must be neutral (to avoid already having been detected) and its mass is constrained by accelerator searches and theoretical considerations of thermal freeze-out to lie in the range 50 GeV to a few TeV. The relic density is determined when annihilations and pair production go out of thermal equilibrium in the early universe at $T \sim m_x/20k$, and one infers that $\Omega_x \propto \sigma_{\text{ann}}$, where $\sigma_{\text{ann}}$ is the annihilation cross-section extrapolated to the low temperature limit. For typical weak interaction values of $\sigma_{\text{ann}}$, one finds that $\Omega_x \sim 0.3$ is required to account for the dark matter content of the universe. Via studying a grid of SUSY models, one can infer a range of particle masses from the annihilation cross-section. Were it not for the accelerator bounds on the particle masses, the uncertainty in $m_x$ would span some 5 orders of magnitude.

The annihilation cross-section and particle mass is constrained. So also is the elastic scattering cross-section once the annihilation cross-section is specified. This means that one can now consider possible detection schemes. The obvious one is direct detection by elastic scattering. Use of annual modulation of the incident flux on a terrestrial detector has led to a tentative detection (DAMA) that requires an implausibly large cross-section given the suite of minimal SUSY.
models and is marginally inconsistent with another experiment (CDMS). Annihilations result in hadronic jets that decay into gamma rays, high energy electron-positron pairs, proton-antiproton pairs and neutrinos, all of which are potentially detectable as galactic halo signals. The EGRET gamma ray detector on CGRO has reported a diffuse high latitude gamma ray flux that can only be accounted for by annihilations if the halo is clumpy by a factor \( < n^2 > / < n >^2 \sim 100 \) (Calcaneo-Roldan and Moore 2000). In fact, the observed signal has a spectral signature that does not resemble that expected for annihilations. Presumably it is due to unresolved distant sources.

Another possible signature of CDM is associated with a feature in the cosmic ray positron spectrum at very high energy. The HEAT experiment reported a feature near 100 GeV that, if real, cannot be explained by secondary interactions between cosmic rays and the interstellar medium. Annihilation products of a 100 GEV neutralino would provide an excellent fit to the data, except that one requires the annihilation cross-section to be boosted by a factor \( \sim 100 \) relative to typical models. Clumpiness in the dark halo again provides a possible explanation in terms of a WIMP signal (Baltz and Edsjo 1999).

Perhaps the most exciting prospect comes from the Galactic Centre, where annihilations may already have been seen. The supermassive black hole at the Galactic Centre of \( 2.6 \times 10^6 \)M\(_\odot\) most likely formed by baryonic dissipation within the already existing dark halo. If the growth process is approximately adiabatic, the neutralinos form a central cusp with slope \( \rho \propto r^{-\gamma'} \), where \( \gamma' = \frac{3 - 2\gamma}{2 - \gamma} \), and the central dark halo cusp slope is \( \gamma \). High resolution halo simulations suggest that \( \gamma \approx 1.5 \), but black hole merging softens the initial CDM cusp to \( \gamma \approx 0.5 \). Even if the cusp were initially destroyed and were isothermal, \( \gamma \approx 0 \), the spike has \( \gamma' > 1.5 \) and the annihilations therefore diverge within the zone of influence of the black hole, at a radius \( \sim GM_{bh}/\sigma^2 \sim 0.1 \) pc, down to about 10 Schwarzschild radii, \( \sim 10^{-6} \)pc.

Signals from the enhanced annihilations may already have been detected (Bertone, Sigl and Silk 2001). The radio flux from Sag A*, the unidentified source at the Galactic Centre, can be accounted for in spectral shape by the annihilation signal from electron-positron pairs undergoing synchrotron radiation, which is self-absorbed. The normalization depends on what assumes about the magnetic field near the SMBH as well as on the central cusp profile. One can eliminate the uncertainty in modelling the magnetic field by calculating the flux of gamma rays, and the spectral distribution of the EGRET gamma ray flux from the unresolved source at the Galactic Centre can be explained. To simultaneously account for the gamma ray flux as well as the synchrotron flux from Sag A*, it is necessary to adopt a magnetic field that is below the equipartition value by a factor of 10 or so.

All of this is necessarily highly speculative. Future observations may greatly help in pinning down the CDM characteristics. Annihilations also generate high energy neutrinos. These propagate freely from the vicinity of the SMBH at the Galactic Centre, and detection would provide unambiguous support for annihilating WIMPs. The predicted fluxes are within the anticipated sensitivity of the ANTARES neutrino detector, now under construction.

In summary, supermassive black holes, for better or for worse, are intimately connected with the process of galaxy spheroid formation. Whether they aid and abet formation of the first stars remains a mystery. There are certainly dynamical and most likely astrochemical links. Given the unahmed array of challenges that CDM is facing in its canonical version, as formulated by so-called semi-analytical galaxy formation, it is tempting to appeal to a totally new ingredient in formulating galaxy formation theory to help resolve these issues. It remains to be seen whether the ultimate answer lies in the dynamical feedback of SMBH formation and evolution on dark halo cores, or on a new prescription that modifies the physics of CDM, or possibly in fundamental physics whereby on large scales unanticipated changes in 4-d Einstein gravity may be appearing, such as might be associated with the influence of higher dimensions. My preference is for the first of these alternatives, but observations will be the ultimate arbiter.

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