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Dark Galaxies and Lost Baryons

Edited by

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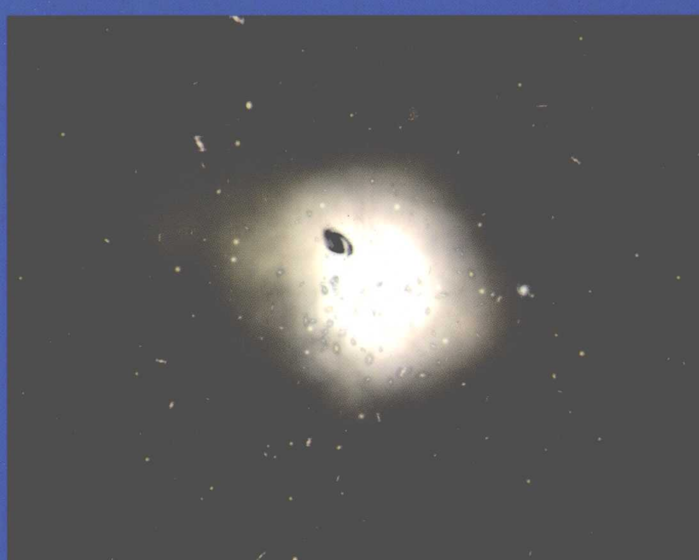
Michael J. Disney



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DARK GALAXIES AND LOST BARYONS

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Edited by

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DARK GALAXIES AND LOST BARYONS

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COVER ILLUSTRATION:

This picture was created by Rhys Taylor to represent x-ray emission from 'lost baryons' in a galaxy cluster. Overlaid are the normal easily visible cluster galaxies and one dark galaxy.

Preface

We cosmic explorers belong to an extraordinary generation. Like Columbus who found exotic seed-pods washed up on the Irish shore we have reasons to believe there is an immense continent out beyond the horizon waiting to be found. It is now almost thirty years since Faber and Gallagher concluded their 1979 Annual Reviews article on galaxy masses with *'....we think it likely that the discovery of invisible matter will endure as one of the major conclusions of modern astronomy.'*

In the mean time observational astronomy has taken extraordinary strides, in wavelength range, in sensitivity, in spatial and spectral resolution, and in multiplexing information. It's as if Columbus' generation had reached the steam ship in a single generation. And yet the dark continent still beckons, still lies out there beyond the present range.

This seemed an appropriate moment to us, and the IAU to take a look at what we have learnt, or failed to learn about the 'Dark Universe' in the mean time, and what we can hope for in the immediate future. This has meant bringing together explorers from very different fields, using very different techniques: Hydrogen line radio astronomers looking for gas clouds and dark galaxies; x-ray observers looking for hot inter-galactic gas; quasar spectroscopists interpreting absorption lines from intervening invisible matter; lensing experts hoping to decipher the presence of dark matter from the distribution of light; optical spectroscopists following the dynamics of stars in nearby galaxies; image analysts looking for ever dimmer structures at any wavelength; computer artists simulating imagined worlds. The reports of their work are all here.

There are three tasks for all of us: to build new instruments; to find new clues; and to interpret what we observe. All three are challenging, but especially the last. Astronomical clues are most often weak and frequently complex. The interpretation will then depend on prior assumptions, admitted or un-admitted, which not all will share, and this will lead, as it did in this lively conference, to hot debates. We wish we could have included more of the substance of the debate in the proceedings. Instead we include a list of controversies at the end, with pointers to the opposing opinions. A flavour of the nature of the issues and discussions can be found in the article written for *Science* by Adrian Cho (Science, 2007, 317, 594).

This list of current controversies reminds us that this meeting was to some extent a continuation of the earlier IAU colloquium 171 'The Low Surface Brightness Universe', also held in Cardiff back in 1998. This also left a list of unsettled controversies which we include for comparison. We let the reader decide were progress has and has not been made.

We would like to thank all the participants for making it such a stimulating meeting. Living in an epoch where something like 98% of the matter predicted by cosmology remains undetected, is both a challenge to observers and an embarassment to cosmologists. We hope these proceedings will be a stimulent to them both.

Jon Davies and Mike Disney,
Cardiff University, September, 2007

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Table of Contents

Preface xi

Organizing committee xii

Conference participants xiii

DARK GALAXIES AND LOST BARYONS

The HI that Barked in the Night 1
M. J. Disney

The Detection of Dark Galxies in Blind HI surveys 7
J. I. Davies

Red Haloes of Galaxies – Reservoirs of Baryonic Dark Matter? 17
E. Zackrisson, N. Bergvall, C. Flynn, G. Ostlin, G. Micheva and B. Caldwell

Constraints on Dark and Visible Mass in Galaxies from Strong Gravitational Lensing 26
S. Dye and S. Warren

Lost Baryons at Low Redshift. 35
S. Mathur, F. Nicastro and R. Willimas

Observed Properties of Dark Matter on Small Spatial Scales 44
R. F. G. Wyse and G. Gilmore

The Mass Distribution in Spiral galaxies 53
P. Salucci

Connecting Lost Baryons and Dark Galaxies via QSO Absorption Lines 63
T. M. Tripp

ALFALFA: HI Cosmology in the Local Universe. 73
R. Giovanelli

The ALFALFA Search for (Almost) Dark Galaxies across the HI Mass Function 83
M. P. Haynes

HI Clouds Detected Towards Virgo with the Arecibo Legacy Fast ALFA Survey 93
B. R. Kent

Cosmic Variance in the HI Mass Function. 103
S. E. Schneider

The Arecibo Galaxy Environments Survey – Potential for finding Dark Galaxies and Results so far. 112
R. F. Minchin et al.

Free-Floating HI Clouds in the M81 Group. 120
E. Brinks, F. Walter and E. D. Skillman

Where are the Stars in Dark Galaxies 127
J. L. Rosenberg, J. J. Salzer and J. Cannon

The Halo by Halo Missing Baryon Problem. 136
S. S. McGaugh

The Local Void is Really Empty 146
R. B. Tully

Voids in the Local Volume: a Limit on Appearance of a Galaxy in a Dark Matter Halo 152
A. V. Tikhonov and A. A. Klypin

Dim Baryons in the Cosmic Web 157
C. D. Impey

A Census of Baryons in Galaxy Clusters and Groups 167
A. H. Gonzalez, D. Zaritsky and A. I. Zabludoff

Statistical Properties of the Intercluster Light from SDSS Image Stacking 176
S. Zibetti

QSO Strong Gravitational Lensing and the Detection of Dark Halos 186
A. V. Maccio

Strong Gravitational Lensing: Bright Galaxies and Lost Dark-Matter 196
L. V. E. Koopmans

Mapping the Distribution of Luminous and Dark Matter in Strong Lensing Galaxies 206
I. Ferreras, P. Saha, L. L. R. Williams and S. Burles

Tidal Debris Posing as Dark Galaxies 216
P. Duc, F. Bournaud and E. Brinks

Numerical Simulation of the Dwarf Companions of Giant Galaxies 226
A. H. Nelson and P. R. Williams

Delayed Galaxies 231
C. Struck, M. Hancock, B. J. Smith, P. N. Appleton, V. Charmandaris and M. Giroux

Probe of Dark Galaxies via Disturbed/Lopsided Isolated Galaxies 235
I. D. Karachentsev, V. E. Karachentseva, W. K. Huchtmeier, D. I. Makarov and S. S. Kaisin

Star Formation Thresholds 247
J. Schaye

Scaling Relations of Dwarf Galaxies without Supernova-Driven Winds 256
K. Tassis, A. V. Kravtsov and N. Y. Gnedin

Star Formation in Massive Low Surface Brightness Galaxies 266
K. O'Neil

Linking Clustering Properties and the Evolution of Low Surface Brightness Galaxies. 274
D. J. Bomans and S. D. Rosenbaum

Too Small to Form a Galaxy: How the UV Background Determines the Baryon Fraction 279
M. Hoeft, G. Yepes and S. Gottlöber

Star Formation in Damped Lyman α Selected Galaxies 284
L. Christensen

Dark-Matter Content of Early-Type Galaxies with Planetary Nebulae 289
N. R. Napolitano et al.

Hunting for Ghosts: Low Surface Brightnesses from Pixels 295
R. Scaramella and S. Sabatini

Baryonic Properties of the Darkest Galaxies 300
E. K. Grebel

The Dwarf Low Surface Brightness Population in Different Environments of the Local Universe 311
S. Sabatini, J. I. Davies, S. Roberts and R. Scaramella

Mass Modelling of dwarf Spheroidal Galaxies 321
J. Klimentowski et al.

Evolution of Dwarf Galaxies in the Centaurus A Group 326
L. Makarova and D. Makarov

A Flat Faint End of the Fornax Cluster Galaxy Luminosity Function 331
S. Mieske, M. Hilker, L. Infante and C. Mendes de Oliveira

Can Massive Dark Halos Destroy the Discs of Dwarf Galaxies? 336
B. Fuchs and O. Esquivel

"Dark Galaxies" and Local Very Metal-Poor Gas-Rich Galaxies: Possible Interrelations 341
S. A. Pustilnik

Morphology and Environment of dwarf Galaxies in the Local Universe 346
H. B. Ann

Arecibo Survey of HI Emission from Disk Galaxies at Redshift z$\sim$0.2 348
B. Catinella, M. P. Haynes, J. P. Gardner, A. J. Connolly and R. Giovanelli

AGES Observations of Abel 1367 350
L. Cortese et al.

Radio Observations of AGN in Low Surface Brightness Galaxies 352
M. Das, S. S. McGaugh, N. Kantharia and S. N. Vogel

Low Surface Brightness Galaxies Around the Hubble Deep Field South 354
L. Haberzetti, D. J. Bomans and R.-J. Dettmar

Spitzer Observations of Tidal dwarf Galaxies 356
S. J. U. Higdon and J. L. Higdon

The True Surface Mass density of Cold Dark Matter Halos 358
J. Holopainen et al.

Warps in Galactic Disks 360
G. I. G. Jozsa, F. Kenn, U. Klein and T. A. Oosterloo

A 500 kpc HI Tail of the Virgo Pair NGC4532/DDO137 Detected by ALFALFA 362
R. A. Koopmann

Virgo Early-Type Dwarfs in ALFALFA 364
R. A. Koopmann

Neutral Hydrogen Gas in Star Forming Galaxies at z=0.24 366
P. Lah et al.

Deciphering Quasar Millilensing – How to Distinguish Between Dark and Luminous Lenses 368
H. Lietzen, C. Flynn, E. Zackrisson and P. Nurmi

Dark Matter Problem in the Local Supercluster 370
D. Makarov and I. Karachentsev

The Distribution of ALFALFA Galaxies 372
A. M. Martin

Investigating the Relationship Between the Hot Gas and the Dark Matter Components of Galaxy Clusters 374
L. C. Powel, S. T. Kay, A. Babul and A. Mahdavi

On the Probability for Sub-Halo Detection through Quasar Image Splitting 376
T. Riehm, E. Zackrisson, K. Wiik and O. Moller

Tidal Influences on Cluster Dwarf Evolution 378
R. Smith, J. I. Davies and A. Nelson

The Chemical Enrichment of the Diffuse Gas in the Outer Galaxy and the Abundance Gradient of the Milky Way 381
L. Song, T. M. Tripp, D. V. Bowen and K. R. Sembach

The ALFA Zone of Avoidence Survey: Results from the Precursor Observations. 383
C. M. Springob et al.

ALFALFA in the Leo Region: Looking for Missing Satellites in HI 385
S. Stierwalt

Dark Galaxies: How about this one? 387
C. Struve, G. I. G. Jozsa, F. Kenn, U. Klien and G. Gentile

Searching for Dark Galaxies: The AGES VC2 Region 389
R. Taylor, R. Auld, L. Cortese, J. Davies and R. Minchin

The Northern HIPASS Optical/IR Catalogue (NOIRCAT) 391
O. I. Wong, R. L. Webster, M. Waugh, V. A. Kilborn and L. Stavely-Smith

The MareNostrum Galaxy Formation Simulation Project 393
G. Yepes, L. Martinez-Vaquero, A. Khalatyan, S. Gottlöber, M. Hoeft and R. Teyssier

Constrained Simulations of the Local Universe 395
G. Yepes, L. Martinez-Vaquero, Y. Hoffman, S. Gottlöber and A. Klypin

The Detectability of Dark Galaxies Through Image-Splitting Effects 397
E. Zackrisson, T. Riehm, H. Lietzen, O. Moller, K. Wiik and P. Nurmi

IAU244 Controversies and Provocative Statements 399

Author index 403

Object index 405

Subject index 406

Dark Galaxies and Lost Baryons
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The HI that Barked in the Night

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Abstract. I discuss some of the interesting discoveries gradually emerging from the HIPASS HI survey. Why were so very few dark clouds and dark galaxies identified? Could that be partly due to optical misidentifications? In some cases yes. Will Arecibo overcome some of the deficiencies of HIPASS? I argue not because large telescopes are ill suited to blind surveys. I discuss the problem of Inchoate Galaxies which can be neither young nor old, and the constancy of HI column density found amongst all sources turning up in blind HI surveys. Could some of these unexpected phenomena be the result of Spin Temperature Freezeout? If so there is a lot more HI out there than we imagined.

Keywords. Galaxies: formation, Cosmology: dark matter

1. Introduction

It's almost exactly 10 years since HIPASS saw first light and this seems a suitable moment to look back and reflect on what it has taught us so far and to ask what we have still to learn. Considering that it was three orders of magnitude faster than its predecessors at making blind HI surveys it will not be surprising if it takes us quite some time to digest some of its most important results. Not the least of these are its negative results, such as its failure to discover the large number of HI clouds un-associated with optical counterparts which we had anticipated when we began. Of 4000 plus southern HIPASS sources not one appears to be lacking a plausible optical counterpart (Doyle *et al.* 2006). Hence my title. Has all the intergalactic HI really produced stars – which seemed very unlikely to us when we began - or are there subtler forces at work? Are Dark Galaxies containing HI really absent from the universe or could we be fooling ourselves? And will successor multibeam receivers, fitted to larger telescopes like Arecibo, render HIPASS obsolete? My theme is that caution and thoughtfulness should be our watchwords for now. Particularly so when optical follow up observations to very few HIPASS sources have been published so far.

2. The identification of optical counterparts in HI surveys

Because we have radial velocities as well as positions it is all too easy to convince oneself that a bright galaxy near the HI position, which has just the right optical velocity as well, is in truth the source of the HI emission - when it is not. Dont forget that galaxies are strongly clustered in redshift space too. And if Intergalactic Gas Clouds (IGCs) and Dark Galaxies (DGs) are clustered with visible ones, as seems plausible, they will generally have bright companions of the 'right' radial velocity. A cautionary tale here was the early claim by QSOAL astronomers who found a bright galaxy of the right radial velocity associated with every low redshift absorption system. Subsequent careful follow up work has shown, in most cases, that insignificant dwarfs and Low Surface Brightness Galaxies, clustered with the bright galaxies, were actually responsible.

Position off-set $d\Delta\Theta$ (kpc)	Probability of finding a random galaxy
50	0.8
30	0.4
10	0.1

Table 1. The probablity of finding galaxies at different position off-sets.

We shall now estimate the probability of finding a random optical galaxy within a given distance, in both angular and redshift space, of any given HI source. We shall assume, as the observations clearly suggest, that optical galaxies and HI sources are clustered together. For a HIPASS source the acceptable volume (V_{acc}) in which an optical counterpart could lie is a long thin cylinder, centred on the source, with its long axis, set by the radial-velocity uncertainties, along the line of sight. For a source at a typical radial velocity $\approx$ 2000 km s^{-1} the angular uncertainties in position (up to 5 arcmins) correspond to $\approx$50 kpc, while the velocity uncertainties ΔV amount to $H_O \Delta V$ ($\approx$30 km s^{-1}) or half a Mpc. Given the correlation function:

$$p(r)dV = n_0 dV(1 + \xi(r)) \tag{2.1}$$

where $\xi(r) = (r/r_0)^{1.8}$ and n_0 is the average number of plausible galaxies per Mpc^{-3}, it is possible to integrate the probability of finding a random galaxy within the volume V_{acc} of the acceptable cylinder. To a very good approximation the number within an angular distance $\Delta\theta$ of the source, at distance d, is given by:

$$N[< d(Mpc)\delta\theta(rads)] \approx 1.8 n_0 r_0^{1.8} (d\delta\theta)^{1.2} \tag{2.2}$$

where $r_0 \approx 8$ Mpc. Notice that the number is only weakly dependent on $\delta\theta$ (because of the strong correlation) and dependent on the radial velocity uncertainty not at all. This last is counter-intuitive but arises from the long thin shape of the cylinder. The ends of the cylinder are so very far from the centre that finding highly clustered galaxies within the ends is very unlikely.

To turn equation 2.2 into numbers it is necessary to adopt an optical Luminosity Function for the putative galaxies.

If we adopt the Blanton *et al.*, (2003) LF, and if we are prepared to accept as our identification an optical galaxy up to 3 mags below M* then Table 1 gives the probability of finding such a random galaxy within an angular size distance $\Delta\Theta$ (radians) of the 21-cm source, where d is the distance of the source away from us. Now the positional uncertainty for radio centroids in HIPASS is typically 1.3 arc mins, (Zwaan *et al.* 2004 and Meyer *et al.* 2004) which at a typical source distance of 2000 km s^{-1} corresponds to a $d\Delta\Theta$ of 10 kpc. But sources are sometimes identified up to 5 (Doyle *et al.* 2006) and even 7 (Wong *et al.* 2005) arc mins away from the radio centroids. It must be clear from Table 1 that the possibility of misidentifying an IGC or a DG with a plausible optical galaxy must be rather high and that there may still be many such hidden in the HIPASS catalogues. The obvious question then is: 'Will the new surveys with Arecibo, with its much improved sensitivity and resolution, overcome the difficulties of HIPASS?'. The answer, to the surprise of many, is 'No'. Why not? Because bigger telescopes find the bulk of their sources at a correspondingly larger distance away where they lose their advantages in angular resolution, beam filling and sensitivity. In other words they will simply find the same sources with the same problems, but further away.

3. Why big telescopes are ill suited to blind HI surveys

The fact that a big dish is undoubtedly so much better for examining a source already known cannot be used to argue that it is equally better for making blind surveys. It has to pay two prices for its smaller beam: (i) less sky coverage/unit time (obv.) and (ii) a noisier sky/unit area (see below). The first limits its volume coverage for sources of a given M_{HI}, the second its column-density sensitivity (more subtle). The 3 governing equations are:

$$d_{max}(M_{HI}) \approx M_{HI}^{1/2} D t^{1/4} \tag{3.1}$$

where D is the dish diameter, d the distance and t the integ.time/beam which is obvious, given that system noise dominates and is independent of D. The survey speed is given by:

$$\frac{Vol(M_{HI})}{T} \approx M_{HI}^{3/2} D t^{-1/4} N_b \tag{3.2}$$

where N_b=No.of multibeams/tel. This equation follows from equation 3.1. Note the temptation to use short integration times to increase the number of sources found. There being no such thing as a free lunch, there is a price to pay however, a price which follows from the next, more subtle, equation for the column density sensitivity:

$$N_{HI} \approx t^{-1/2} \tag{3.3}$$

Equation 3.3 is independent of D, which is seldom acknowledged by experienced HI observers, who apparently seem to believe in free lunches. It follows (see below) *because larger tels. project the same system noise into smaller beams, and hence have to work against an apparently noisier sky.*

As an example we can compare the Arecibo blind surveys ALFALFA and AGES against HIPASS.

(1) ALFALFA maximises the source-finding speed by reducing t per beam: Speed $\frac{ALFALFA}{HIPASS} \propto Dt^{-1/4} N_b = \frac{305}{64} \times \frac{28sec}{450sec}^{-1/4} \times \frac{7}{13}$ ≈5 times faster for a given M_{HI}. Its survey depth d_{max} (see eq. 3.1) is 2.4 times greater than HIPASS so the number of sources it will find/unit area will be $(2.4)^3$ =14 times greater. However the sky coverage (as a fraction of the total) is 0.23 times less, so the total number of sources found of a given M_{HI} (e.g. low mass clouds) will only be $14 \times 0.23 = 3.2$ times greater, which is hardly significant. Worse still, because of its low integration time/beam (28 sec) its column density sensitivity (see eqn. 3.3) will be 4 times worse than HIPASS, making it unsuited to searching for such clouds anyway. Since its typical sources will be 2.4 times further away it has a slight resolution advantage over HIPASS of $[305/(64 \times 2.4)]=2$ times better, which will help with source identification. Altogether though it is hard to see how ALFALFA will afford any significant scientific advance beyond HIPASS.

(2) AGES maintains the same N_{HI} (i.e. surface brightness) sensitivity as HIPASS by using comparable integration times. Its survey speed is then $\propto DN_b = \frac{305}{64} \times \frac{7}{13} = 2.5$ times faster but its typical sources are 305/64= 4.75 times further away. However since it is targeted (unlike ALFALFA) at specific targets of known redshift (e.g. clusters), it does have 305/64 times better physical resolution at that redshift and it can use unused correlator capacity to obtain higher velocity resolution, which can be useful for finding narrow-line sources ($t \rightarrow t\Delta v$ in many of the above equations because of the Bandwidth Theorem). Again though one cannot expect dramatic improvements over HIPASS. My point is not to criticize these surveys but to plead that much of the time at Arecibo