STATEMENT ON RESEARCH INTERESTS

BY JUAN E. CABANELA

Today, in the first decade of the 21st Century, astrophysicists believe we have an excellent understanding of what happened between 10^{-43} seconds and 380,000 years after the Big Bang. After 380,000 years the Universe had cooled off enough such that electrons and protons can form neutral hydrogen atoms without immediately reionizing. Because the cross-section of hydrogen atoms to photons is considerably smaller than the comparable cross-section of free electrons, the baryonic matter in the Universe decoupled from the radiation field and the Universe's evolution became "matter-dominated." When this happened, matter was no longer supported by radiation pressure and could collapse under the force of gravity to form galaxies and stars. Unfortunately, this is also the point at which our understanding of the Universe's evolution becomes noticeably sketchier. Because about 90% of the matter in the Universe is non-baryonic dark matter[1], the evolution of the Universe became dominated by material whose nature we haven't been able to precisely pin down. Astrophysicists believe that "normal" baryonic matter fell into the gravitational wells of dark matter aggregations during the first billion years after the big bang, driving the formation of galaxies and large-scale structures (*e.g.* clusters and superclusters of galaxies). However, without a detailed understanding of the character of dark matter, we can only model the evolution of the Universe based on various dark matter models and see which one fits what we see best. My fascination with this era of galaxy formation and the lack of information about its detailed mechanics led me to search for modern "relics" from galaxy and large-scale structure formation that could elucidate this epoch of the Universe's history. I have looked for these "relics" on large (*e.g.* supercluster) scales and am now involved in looking for them on the much smaller scales of our Galaxy. On the way, I have had some interesting "detours" that have proven quite fruitful: (1) statistical measurement of internal extinction in galaxies, (2) the identification and distribution of low surface brightness galaxies, and (3) the identification of the origin of the asymmetry observed in thick disk stars in the Galaxy.

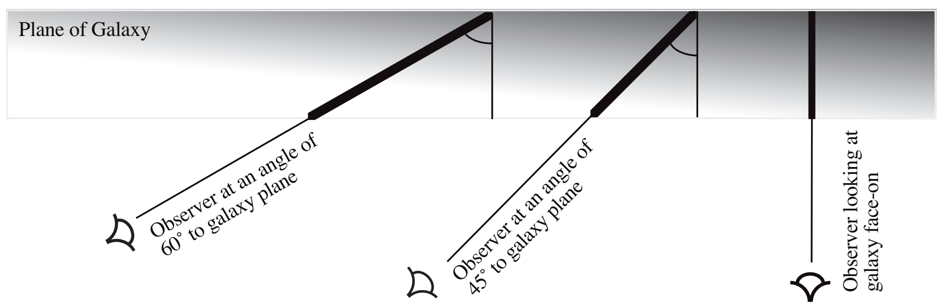
STATISTICAL MEASUREMENT OF INTERNAL EXTINCTION DUE TO DUST IN GALAXIES

My first research project in graduate school started when I read about the attempts of some Japanese astronomers to see if galaxy angular momentum (spin) vector alignments caused by the formation of large-scale structure could still be observable today. If the Universe's structure formed "top-down," large superclusters forming first and then fragmenting into galaxies, galaxies should exhibit a preferred major-axis orientation along the original angular momentum axis of the supercluster. If structure formed was "bottom-up", with galaxies forming first and then grouping to form superclusters, no such obvious trend would be expected in galaxy major-axis orientations. I realized that the Minnesota Automated Plate Scanner Catalog of the Palomar

[1] The modern understanding of dark matter is that it is a non-baryon form of matter that does not interact via electromagnetic forces, but does interact gravitationally (and possibly via the weak nuclear force, depending on the model) with "normal" baryonic matter.

Observatory Sky Survey (hereafter, MAPS catalog)[2] was an excellent tool for investigating this problem, since it had detailed information on galaxies covering most of the northern sky. All I had to do was pull the right information out of catalog, so I plunged into learning *C* programming and the perils of the Unix command line. Within a year I had collected machine-measured axial ratio and position angle[3] information for over 1200 galaxies in the field of the Pisces-Perseus Supercluster. I thoroughly probed this dataset looking for the predicted major-axis alignments as well as using the Arecibo 305 meter telescope to observe a subset of over 50 edge-on galaxies in order to precisely determine their spin vector orientations. These investigations revealed that any remaining primordial "relic" hidden in the spin vector orientations of galaxies had to be very weak.[4]

At this point, I began a "detour" that would turn into my Ph.D. thesis. One of the critical issues in large statistical studies is sample selection. In extragalactic astronomy there are a lot of biases that can "slip in" if one is not careful. My work on the distribution of galaxy orientations revealed a major problem: Most astronomers realized that dust in galaxies could affect their observed brightness and color. However, few realized that the dust content and its distribution within galaxies could also affect their observed diameters!



We observe galaxies at different orientations to our line of sight. As shown in the Figure to the right, as our line of sight changes, this can affect the length of our line of sight through the galaxy. If galaxies were completely dust-free, their total observed brightness would be independent of line of sight, since none of the light would be blocked by dust. However, as our viewing angle becomes more "edge-on," more stars would exist along any line of sight through the galaxy and thus it would have a larger major-axis diameter. This means any "diameter-limited" sample of galaxies is biased toward picking up less-luminous edge-on galaxies than face-on galaxies. In the opposite extreme, if galaxies were optically thick with dust distributed such that you could only observe the outer "crust" of stars, then they would behave like Frisbees and have constant diameter regardless of their orientation to our line of sight. Since we don't know the

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[2] A full description of the MAPS catalog can be found in Cabanela, J.E., Humphreys, R.M., Aldering, G., Larsen, J.A., Odewahn, S.C., Thurmes, P.M., and Cornuelle, C.S. 2003, PASP, **115**, 837. I was co-investigator on a NASA AISRP project to distribute archived copies of the final version of the MAPS catalog, containing over 89 million stars and galaxies, on DVD–Rs. The MAPS catalog is also available online at *http://maps.cabanela.com/* and *http://aps.umn.edu/*.

[3] Position angle is the angle that the major axis of an object makes relative to the north-south line, measured from north to east. An object's axial ratio and position angle provide information its spin axis orientation.

[4] In fact, the only possible spin vector alignments I observed were weak alignments with large-scale structure in higher density regions, which are likely a more recent phenomenon. We expect enough near collisions with angular momentum exchange in these high density regions that no primordial signal should survive into the present epoch. For more details see Cabanela, J.E. and Aldering, G. 1998, AJ, **116**, 1094 and Cabanela, J.E. and Dickey, J. 1999, AJ, **118**, 46.

distribution and quantity of interstellar dust in galaxy *a priori*, astronomers face a major complication because until we can compensate for the effects of internal extinction on galaxy appearance, we have no way of comparing observations made of galaxies at differing inclination angles.

I realized that I was in a position to investigate the effects of this dust on the observed diameter and brightness of galaxies as a function of inclination and morphological type (*e.g.* spiral, elliptical, etc.). I could do this by using a large sample of galaxies with machine-measured optical parameters to statistically attack the problem.[5] Using a subset of over 9000 galaxies from the MAPS catalog with published redshifts and morphological classifications, I binned the galaxies by inclination angle to see if any trends were seen in their major-axis diameters and luminosities versus inclination. If galaxies were optically thin, we would expect diameters to increase and luminosity to remain constant as the inclination angle to the line of sight increases. If galaxies were optically thick, we would expect diameters to remain constant and the luminosities to drop in the more edge-on populations. My thesis results demonstrated a surprising trend in that tightly wound spirals did not appear to be any more optically thick than the loosely wound spirals.

In the last three years, the availability of the public data from the Sloan Digital Sky Survey (SDSS)[6], which has more accurate photometry and much more extensive redshifts than any previous large sky survey, has made it possible to return to this field with a vengeance. My summer undergrads, Supreet Sidhu (Swarthmore College) and Wendy Bennett (Drake University), each spent a summer obtaining the SDSS data and then writing code to properly process and clean it up. Since no human can classify the millions of objects in the SDSS visually, we switched from visual morphological classifications to the use of Sérsic indices[7] as an indicator of galaxy morphology. As of fall of 2005, using the latest public data release of the SDSS, we are attacking the internal extinction problem with a sample of over a quarter million galaxies![8] While still ongoing, it appears that this research supports my original Ph.D. thesis results that the level of internal extinction in spiral galaxies is independent of morphological type. Furthermore, work by Adolf Witt (U Toledo) and his collaborators suggests there may be a theoretical basis for these surprising results.

While understanding the internal extinction of galaxies may not seem to play a direct role in comprehending the origins of galaxies, is certainly an issue that needs to tackled before a proper examination of the galaxian "relics" of galaxy formation can be made.

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[5] Machine measurement is critical because the human eye/brain do a wonderful job of introducing physiological biases in measurements of diameters since it is easier to see spiral arm patterns in face-on galaxies versus edge-on galaxies.

[6] See *http://www.sdss.org/* for details.

[7] Sérsic indices, n, are computed by a fit of the galaxy's surface brightness profile, $I(r)$, with the function

$$I(r) = I_0 \exp\left[\left(\frac{r}{r_0}\right)^{\frac{1}{n}}\right].$$

Spiral disks have exponential light profiles, so $n\sim 1$ whereas elliptical galaxies are observed to have $n\sim 4$.

[8] A sample 25 times larger than the sample I used just five years earlier in my Ph.D. thesis!

THE IDENTIFICATION AND DISTRIBUTION OF LOW SURFACE BRIGHTNESS GALAXIES

In the last 5 years, cosmology has become a precision science with many cosmological parameters determined to within a few percent. The MAXIMA, BOOMERANG, and WMAP observations of the Cosmic Microwave Background angular power spectrum indicate that we live in a spatially flat universe (Ω_{total}=1.02±0.02). Recent measurements[9] of the deuterium abundance in distant hydrogen clouds strongly suggest that Big Bang nucleosynthesis only produced enough baryons to account for 4% of the density of the universe.[10] Even so, we have realized we haven't even found most of them. Only about 10% of the baryons we know should exist can be accounted for in the observed stars and gas in galaxies! During the last two decades it has become clear that many of these baryons could be hiding in plain view in Low Surface Brightness galaxies (LSBs).

LSBs are believed to be galaxies in which star formation has operated at a much slower rate than in "normal" galaxies, most likely due to their very low gas density. This low star formation rate in LSBs results in a low surface brightness and their observed high hydrogen gas mass fractions. Their low surface brightness also makes them very difficult galaxies to detect. Recent measurements of the extragalactic background light[11] suggest ~33% of baryons are in stars, which is a factor of 2 to 3 times higher than the number of stars actually observed in galaxies thus far. This suggests a lot of the baryons in the universe, at least those trapped in luminous stars, could be hiding in low surface brightness galaxies or possibly free floating in intergalactic space (having been gravitationally ejected from their birthplaces in galaxies). Thus, it is possible that LSBs are a major (and thus far mostly unobserved) baryon repository in the universe.

As I worked on finishing the final version of the MAPS Catalog, I was looking for data mining projects to probe this new catalog with. John Dickey and I cross-identified the MAPS catalog with his HI maps of galaxy clusters and discovered that the optical counterparts to hydrogen-rich galaxies (potential LSBs) laid on the "blue edge" of a color-magnitude diagram constructed using MAPS catalog data.[12] Follow-up observations of these "blue edge" galaxies at the Arecibo 305 meter radio telescope confirmed the converse, that the majority of "blue edge" are hydrogen-rich and share many properties with LSBs. This discovery provided the first simple automatic method for identifying LSB candidates from an existing optical catalog.

I realized the logical application of our discovery was to test one of the assumptions about the initial density perturbation power spectrum in the early Universe (from which galaxies supposed formed). If the initial power spectrum were Gaussian, the majority of perturbations that survive to the modern era would be smaller ones which would form LSBs.[13] These LSBs would be relatively isolated on small scales (to allow survival of their small density perturbations into modern times), but otherwise they

[9] Tytler, *et al.* 2000, Phys. Rep. **333**, 409

[10] The remaining density of the universe appears to be about 23% [dark, non-baryonic] matter density and 73% vacuum energy density.

[11] Bernstein, Freedman, and Madore 2002, ApJ, **571**, 107

[12] Cabanela, J.E. and Dickey, J.M. 2002, AJ, **124**, 78.

[13] In fact most theoretical models of galaxy formation overproduce small "dwarf" galaxies relative to their observed models. This suggests that if the theorists are correct, that many small galaxies have remained unobserved. If they were LSBs, this could be quite possible.

should trace out the same mass distribution seen in "normal" high surface brightness (HSB) galaxies. Previous studies have supported this prediction through comparisons of the positions of LSBs to HSB galaxies in all sky surveys. But no one has done a detailed study of the comparative distributions of these galaxies in a single supercluster, in large part because the number of known LSBs in any one supercluster is generally small.

I set about to identify a large number of LSBs in the field of the Pisces-Perseus Supercluster. In late 2002, my summer student, Megan Roscioli (Haverford College), and I were granted ~40 hours of observing time at Arecibo, which we used to identify over 100 hydrogen-rich "blue edge" (LSB candidate) galaxies in the Pisces-Perseus Supercluster. We have reduced the HI spectra for our LSB candidates with one immediate result, these LSB candidates are distributed in a similar manner to the known HSB galaxies in the field (See Figure 2). This was not a shock, considering previous studies, but these results are the first clear illustration that LSBs do indeed follow the large-scale structure on smaller scales. Unfortunately, we have been unable to proceed with our planned comparison to the extensive radio observations in this field of the sky by Giovanelli, Haynes, and collaborators because that data remains unpublished. Once that data, covering over 1000 "normal" high surface brightness galaxies in the Pisces-Perseus field, is available, we will make a clearer determination of the trends of surface brightness and neutral hydrogen content versus environmental density than has been previously possible. This will provide stronger constraints on the power spectrum of density perturbations in the early universe with the resulting implications for the formation of galaxies.

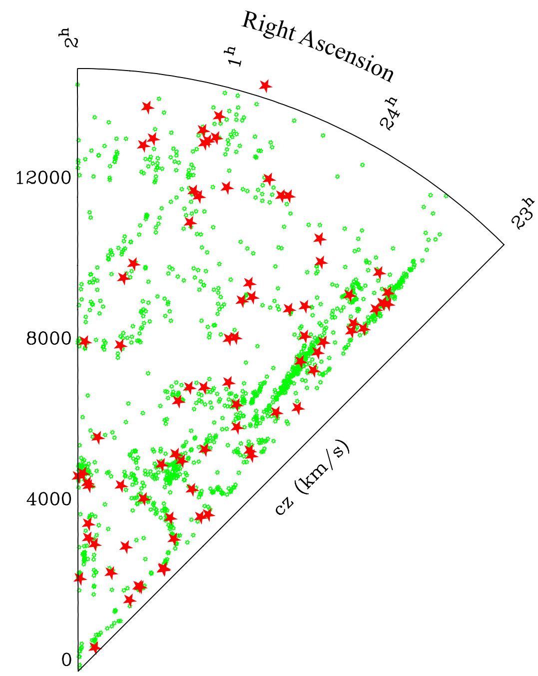

Figure 2: A plot of the redshift space distribution of LSB candidates in the PPS field [large stars] versus previously cataloged "normal" galaxies [small stars] based on HI spectra. Recalling redshift is roughly proportional to distance via Hubble's law, we can note the fact that LSB candidates appear to deliniate the same structures as "normal" HSB galaxies..

THE ORIGIN OF THE ASYMMETRIC THICK DISK IN THE MILKY WAY GALAXY

Recently I have started to "detour" into work on smaller scales and closer to home, looking at the origin of structures within our own galaxy, the Milky Way. With the completion of the MAPS Catalog, the online availability of the Two Micron All Sky (2MASS)[14] and SDSS Surveys, and the availability of high-speed desktop computers, it is clear that some classical techniques in astronomy could be reapplied with greater power. One of these problems is determining the shape of the Milky Way (a.k.a. the Galaxy)

[14] See *http://www.ipac.caltech.edu/2mass/* for details.

through the distribution of its stars. Over a century ago, the basic technique of star counts was developed by Kapteyn as a way of determining the distribution of stars in the Galaxy. The technique is simple, observe the number of stars in differing brightness levels in different directions in the sky. Then predict the star counts based on a Galaxy model, compare it to the observations, and use this to refine the model. This is precisely the kind of project, involving large numbers of observations and extensive number crunching, which is perfect for the epoch of digital computing.

In the late 1990s, Larsen and Humpheys[15] used star counts in 88 selected 16 square degree (deg^2) fields across the sky and implemented a genetic algorithm to optimize a good Galaxy model fit to the data. This galaxy model then allowed them to "flat field" the Galaxy, removing the expected star counts in each direction in order to look for deviations from the model. From this work came the discovery of an asymmetry in the distribution of thick disk stars on 1st quadrant (Q1) side of the Galactic center versus the opposite 4th quadrant (Q4) side. In four paired fields about 30˚ above the Galactic plane, more thick disk stars are seen in Q1 versus Q4. Parker[16] in her thesis expanded on this work examining star counts of over 6 million stars across 120 sixteen deg^2 fields. As shown in Figure 3, Parker confirmed the thick disk asymmetry for stars 30˚ to 40˚ above the Galactic plane, observing it extended from 20˚ to 60˚ in Galactic longitude. The recently confirmed Galactic bar[17] in the (thin) disk of the Milky Way is about 5 kiloparsecs distant in this direction, whereas the excess thick disk stars are between 1 and 2 kiloparsecs distant (and about 0.5 to 1.5 kiloparsecs above the plane). This implies a major substructure in the thick disk population of stars that doesn't precisely correspond to the observed thin disk features.

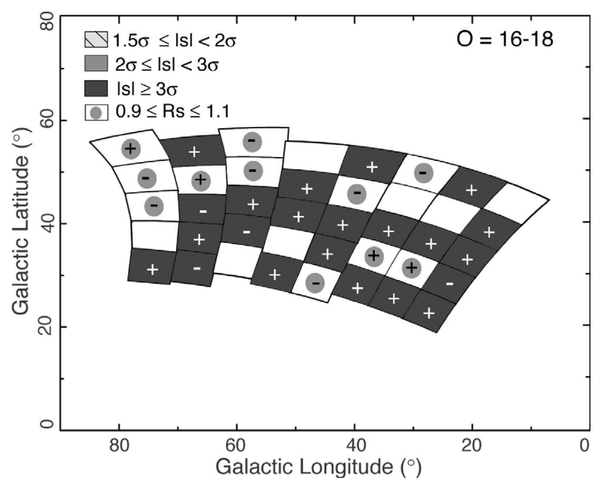

Figure 3: A map in Galactic latitude and longitude for stars selected by their color to be thick disk stars. The plot shows the significance of the excess counts in that field versus the corresponding field in the 4th quadrant (this is Fig. 11 from Parker, Humphreys, and Larsen 2003).

Three possible explanations for the asymmetry are (1) the fossil remnant of a merger, (2) a triaxial thick disk or halo, and (3) interaction of the thick disk/inner halo stars with the bar in the thin disk, possibly in the form of a gravitational "wake" of thick disk stars piling up behind the bar.[18] Stellar spectra for 700 stars in Q1 and Q4 shows that the thick disk stars in Q1 have a significantly slower rotation rate than the corresponding stars in Q4.[19] This, combined with the lack of any spatial overlap with the path of the Sagittarius dwarf through the halo,[20] seemed to eliminate the first explanation.

[15] Larsen, J.A. and Humphreys, R.M. 2003, AJ, **125**, 1958.
[16] Parker, J.E., Humphreys, R.M., and Larsen, J.A. 2003, AJ, **126**, 1346.
[17]The confirmation is based on the GLIMPSE (Galactic Legacy Mid-Plane Survey Extraordinaire) Point Source Catalog of ~30 million mid-infrared sources toward the inner Galaxy (Benjamin, R.A. *et al*. 2005, ApJ, **630**, 149).
[18] Hernquist, L. and Weinberg, M.D. 1992, ApJ, **400**, 80.
[19] Parker, J.E., Humpreys, R.M., and Beers, T.C. 2004, AJ, **127**, 1567.

This discussion of the thick disk asymmetry leads to my current NSF-sponsored (AST-0506853) project. I am a co-PI with Roberta Humphreys (U Minnesota) and Jeff Larsen (US Naval Academy) on a collaborative project to see if the origin of the thick disk asymmetry can be pinned down between the two remaining options. The project has two major components. The first consists of follow-up observations using modern facilities to obtain very faint star counts in selected fields above and below the galactic plane. These deeper counts should allow us to determine the extent of the asymmetry (in depth) and observations below the plane will confirm if the asymmetry there as well, which is an important test for either a triaxial thick disk or gravitational "wake" model. The modern multi-color photometry will also allow better segregation of thick disk stars from other stars than possible with plate-based data. We will also be obtaining spectra for several hundred additional thick disk stars below the plane, again with an eye to confirming the kinematics we see for the asymmetry above the plane are reflected below the plane as would be expected in the preferred models. Our collaboration has already been awarded observing time for the Spring 2006 season: 6 nights on the CTIO 1-m (for wide-field imaging), 3 nights on the CTIO 4-m (for spectroscopy), and some time on the 90-inch on Kitt Peak. These observations are ideal work for undergraduates in that their data reduction, while somewhat challenging, does not require broad theoretical knowledge of the field. In addition to these observations, we also intend to extend our modeling of star counts to incorporate not only as much of the MAPS Catalog as possible (about 600 fields) but also the SDSS catalog (which covers only the steradian around the North Galactic pole, but does so with increased photometric accuracy) and the 2MASS counts (which are all sky and in the near-infrared) in order to construct a much more detailed model of the Galaxy. This model should allow for more precise "flat fielding" of the Galaxy star counts and possibly the discovery of additional asymmetries in the stars counts as might be expected in a spiral galaxy. Understanding the nature of these asymmetries (including the established thick disk asymmetry) should provide valuable clues to their origin and to the mechanisms behind our Galaxy's formation.

While my research interests may seem a bit broad, they can be tied to two themes: (1) the exploitation of the new large astronomical catalogs (MAPS, FIRST, SDSS, 2MASS) as they become available, and (2) the incorporation of observations performed at national facilities (such as Arecibo, Kitt Peak, and Cerro Tololo), in combination with these large catalogs, to further the investigation of relics from the era of galaxy formation. The projects I am interested in don't require large amounts of lab space, just good fast computers and some bright undergraduates to help with the data analysis. Given these resources, it is my hope I can aid in the construction of a detailed model of galaxy formation, allowing us to extend our "confident" understanding of the Universe from 10^{-43} seconds after the Big Bang all the way to modern times.

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[20] Ibata, R., Irwin, M., Lewis, G.F., and Stolte, A. 2001, ApJL, **547**, 133.