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天文光度函数

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摘 要

至少从托勒玫时代以来，天体的计数已成为天文学的一部分。光度函数是作为某一波段的光度或亮度的函数的特定种类的天体数目。而视亮度的相应概念通常叫作计数。虽然有点夸张，但这些工具仍是检验天体物理假设和检验天体物理新概念的强有力的手段。本评论来源于 1995 年 1 月份为 Maarten Schmidt 诞生 65 周年而召集的一次学术会议。可用以研究光度函数的重要天体包括很暗的恒星、γ 射线暴、亮类星体和其他活动星系，及不可见辐射源。特别令人惊奇的是：很暗的恒星少，而很暗的星系数目非常大。一个重要而尚未解决的问题是：我们是否足够好地了解，甚至是否能够足够好地了解星系、星系团、射电和 X 射线源的内禀天体物理性质及其演化，以便用这些天体作为宇宙学和宇宙大尺度结构参数的探针。

关 键 词 恒星：光度函数 — 星系：光度函数 — 星系：活动星系 — 白矮星

Astronomical Luminosity Functions

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Abstract

Counting objects has been part of astronomy at least since the time of Ptolemy. A luminosity function is the number of objects of a particular sort as a function of their luminosity or brightness in some wavelength band. The corresponding concept for apparent brightness is generally called a number count. Though simple-sounding, these tools are remarkably powerful ones for testing astrophysical hypotheses and suggesting new ones. This review has its origins in a conference held in January, 1995, honoring the 65th birthday of Maarten Schmidt. The important kinds of objects whose luminosity functions are useful to study include the very faintest stars, gamma ray bursters, bright

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quasars and other active galaxies, and sources of non-visible radiation. Particularly surprising are the rarity of the faintest stars and the extraordinarily large numbers of very faint galaxies. An important unsettled question is whether we understand, or ever can understand, the intrinsic, astrophysical properties of galaxies, clusters, radio and X-ray sources, and their evolution well enough to use them as probes of cosmology and the large scale structure parameters of the universe.

Key words stars: luminosity function—galaxies: luminosity function—galaxies: active—white dwarfs

1 Introduction

In modern astrophysics one example of a new source is a discovery, two is a confirmation, and three is a well-known class of objects. The next thing we do is to plot a luminosity function–that is,the number of objects as a function of their real (or sometimes apparent) brightness over some wavelength band, *N(L)*. This simple statistical tool is a remarkably powerful one for suggesting new astrophysical hypotheses and ruling out old ones, as became clear during the workshop on Astrophysical Luminosity Functions, convened at the California Institute of Technology in January, 1995, to honor Maarten Schmidt, upon the occasion of his 65th birthday.

While Schmidt is best known for his role in the discovery of quasars, he has also pioneered the use of luminosity functions and closely related statistical concepts as keys to the evolution of populations of stars and galaxies as well as quasars. Schmidt's original statistical concept, $V/V_{\rm max}$,is a sort of moment of $N(L)$. $\langle V/V_{\rm max}\rangle$ of the source population found in some particular survey is defined as the average value of a ratio volumes for each source. V is the volume contained within the distance at which you see a given source; $V_{\rm m}$ is the volume contained within the maximum distance at which the source could have been and still be found in your survey. If the sources are distributed uniformly through space, $\langle V/V_{\rm m}\rangle$ is exactly 0.5. When it is larger, as for quasars, then you know the sources are commoner far away; and when it is smaller than 0.5 (as for gamma ray bursters), then you know the sources are concentrated near you for one reason or another.

There are contexts in which $N(L)$ is itself the most interesting distribution (for instance in the study of white dwarf cooling or the attempt to account for the X-ray background as a sum of sources in active galaxies). In other cases, $N(L)$ is a step toward a physically more important distribution, like numbers of stars as a function of their masses, numbers of solar or stellar flares vs. total event energy, or numbers of earth-crossing asteroids of different sizes.

The shape of a luminosity function can sometimes help distinguish real events from experimental artefacts or determine whether a given set of objects is a discrete, physically coherent population or a mixture. A sudden cut-off in some $N(L)$, if it is not an observational selection effect, can reveal the onset or termination of a physical process, while a sharp feature or peak, if it always occurs at the same luminosity, can function as a distance indicator.

During a panel discussion which concluded the second day of the workshop, luminosity functions or related statistics for more than 40 different kinds of astronomical objects were mentioned at least briefly. Many of the most interesting were the topics of invited review talks and appear in the following sections. Some of the important ones that were not further addressed include (*a*) earth-crossing asteroids, as an indicator of how often and how devastatingly they will hit our planet, (*b*) giant molecular clouds and HII regions, as probes of star foramtion rate under different conditions, (*c*) planetary nebulae and globular clusters, as distance indicators for external galaxies, (*d*) pulsars, as tracers of the time evolution of neutron star magnetic fields and rotation periods, and (*e*) quasar absorption lines, as indicators of structure in the universe further away than we can conveniently study galaxies.

2 Stars, Especially Faint Ones

James Liebert (Steward Observatory) opened the "festspiel" by talking about objects at very low redshift and asking where are the white dwarfs with M_V greater than +16. Main sequence stars continue down to $M_V = +19$ (albeit with very different bolometric corrections), so it cannot be a purely observational problem. Generically, the space density of white dwarfs of different luminosities constitutes a record of the local star formation (and death) rate and of the cooling of degenerate stars once their nuclear energy sources have been exhausted. Thus a shortage of faint white dwarfs would seem to imply either a glitch in our models of cooling or a deficit of stars formed more than a certain number of years ago.

Both explanations remain at least possible, according to Liebert, who discussed carefully the various cooling regimes, their predictions for the luminosity function (e.g. $N(L) \propto L^{-5/7}$ over the intermediate, best-understood regime), and how these depend on white dwarf masses. There is a cross-over between dominant cooling processes at about the luminosity, $10^{-4}L_{\odot}$, where the number density drops, which is, perhaps, suggestive. The cooling model part of the problem can be pinned down with WD luminosity functions in star clusters whose ages are known from their main sequence turnoffs. Among clusters in the Gyr range, there seem to be no surprises. HST data expected soon for older globular clusters will be very important in eliminating erroneous cooling curves as the cause of the sparcity of faint white dwarfs. Meanwhile, the obvious conclusion remains that very few stars formed in the galactic disk (at least at our distance from the galactic center) more than 8–10 Gyr ago.

The observers have not, however, given up, and a recent southern survey by M.-T. Ruiz and her colleagues has unearthed ESO 439–26, with $M_V = +17.6$, more than a magnitude fainter than any of the WDs found on the USNO parallax program. The star is neither anomalously red (V–I=+1.2) nor a halo object (space velocity about 40 $\mathrm{km \cdot s^{-1}}$) .

Jeremy Mould (Mount Stromlo and Siding Spring Observatories–several telescopes but only one spring) focussed on $N(L)$ for halo stars, both in the field and in globular clusters. Here the interesting questions are the shape of the luminosity function, especially at the faint end that might merge into the brown dwarf regime, and whether/how that shape is correlated with stellar age, metallicity, location in the galaxy, or whatever. Such correlated variations of $N(L)$ might be causal and so provide information about the still-mysterious processes of star formation in halos.

Somewhat disconcertingly, there remain large disagreements among observers concerning both the slope of $N(L)$, expressed as a power law, L^{-x}, and the absolute value, even for field stars as bright as $M_V = 6 - 8$. Mould intimated, however, that most observers are now voting for smallish absolute numbers, like 10^{-6} stars·pc^{-3} near $M_V = +6$, rather than O.J. Eggen's value of 10^{-4}. The steepest reported slope is $x = 0.62$, derived by H. Richer and G. Fahlman. This should perhaps be interpreted as contamination by thick disk stars, in light of the recent HST/WFPC2 limit, $x \leq 0.32$, over the range $M_V = 6 - 17$, reported by J.N. Bahcall and others.

Globular cluster luminosity functions have a similar history of confusion, including a claim of strong correlation of x with metallicity, based on very few clusters, and disagreement about whether the last measured point is still rising. A larger sample, compiled by S. Djorgovski *et al.*, leads to a much more complex correlation, in which $N(L)$ is steepest far from the galactic center and far from the galactic plane. Then, when these dependences are removed, a shallower residual one on composition remains, in the sense that lower metallicity goes with steeper $N(L)$. Mould endorsed the correlation and an average $N(L)$ for halo stars that is already turning down again in the observed luminosity range.

Combining ground based and HST results more or less forces us to the conclusion that very little halo dark matter is in faint dwarfs or subdwarfs, unless $N(M)$ rises again suddenly below the minimum mass capable of burning hydrogen (about 0.1 $M_\odot$ for extreme population II composition).

Neill Reid (California Institute of Technology) carried the surveys on down to low mass disk stars. It is tempting to put the punch line first—there aren't very many, and no persuasive, confirmed cases at all of objects in the brown dwarf/Jupiter mass range (except among companions of pulsars and highly evolved cataclysmic variables). Or, as

Reid said, "don't put your daughter on brown dwarfs, Mrs. Worthington." As in the case of faint white dwarfs, an accurate theory of cooling is essential for interpreting the observations. For 10^9 yr or more, stars just above and just below the H-burning mass cut (about 0.085 $M_\odot$ for population I composition) occupy much the same regions of most color-magnitude diagrams.

Searches for brown dwarf field stars and companions (whether using proper motions, radial velocities, or infrared interferometry) have been equally unsuccessful. No candidates has met either the test of having a measured mass less than the burning limit or of having preserved lithium long enough that one knows hydrogen burning could not be underway (stars below about $0.3M_\odot$ are convective throughout). The most promising remaining candidate, GD 165B, unfortunately has no flux at the wavelengths of the lithium lines (though an astrometric orbit mass might be possible if humanity survives long enough). Another handful of recent candidates are, according to D. Kirkpatrick, all probably very young (based on their velocities and distances from the galactic plane) and still in the confused region of the color-magnitude diagram, whatever their masses.

3 Lenses, Bursters, and Related Objects

George Preston (Observatories of the Carnegie Institution of Washington) provided a transition from normal stars to the truly weird by discussing results from two massive survey projects, called HK and OGLE, which have been uncovering all sorts of unexpected aspects of stellar populations in the Milky Way. Preston described his role in these collaborations as money-launderer and struck a note echoed in various ways by several later speakers by claiming he had never won an argument with Maarten Schmidt. The order in which products of the surveys ought to be presented depends on what you think each means. Since neither Preston nor we are quite sure, feel free to rearrange the following sentences any way you wish.

First, the Milky Way unambiguously has a central, stellar bar (whose member stars contribute as both lenses and targets to lensing). It reveals itself as a difference in apparent magnitude of red clump stars (the metal-rich analogue of the horizontal branch) on opposite sides of the galactic center. The population gradient in this region is quite steep. The clump stars are conspicuous in the OGLE field at $b = -4°$ and essentially absent from one at $b = -8°$ studied by D. Terndrup. Age differences are also important. The region at $R = 3.5$kpc (formerly the 4 kpc arm, when the galactic center was further from us) has a ratio of red clump to red subgiant stars of about 1.3, indicating a smaller age than for globular clusters of the same metallicity, where the ratio is about 0.8.

Next, several old open clusters, like Collinder 261, have revealed large numbers of W UMa stars, which are essentially non-existent in clusters less than 1 Gyr old, but also, it begins to seem, rather common in globular clusters. This confirms an earlier conclusion by S. Rucinski that W UMa's make up about one star in 200 in both the field and old open clusters. And then there is a halo field population, previously advertized as blue stragglers (i.e. presumably binaries or binary merger products), which turns out really to consist of stars just the right age and mass to be that color and brightness. But they are of low metallicity. Since the Milky Way hasn't been producing that combination lately, they must be the remnants of a captured dwarf irregular galaxy.

Such captures are fairly common. OGLE has independently confirmed the new Sagittarius dwarf reported by Ibata, Gilmore, and Irwin, only 16 kpc from the galactic center (on the far side from us). It is clearly not long for this world, and there is already evidence of tidal tearing.

RR Lyrae stars in the Sculptor dwarf spheroidal galaxy include the types found in both Oosterhoff I and II globular clusters in the Milky Way. They show a period–color–luminosity relation (tied to location in the galaxy, and presumably, to composition–measurers of H_0 please note!). In addition to the expected sorts of variable stars, the OGLE survey has found a large group of K giants with amplitudes near 0.1mag, periods of 3–100 d, and sinusoidal light curves suggestive of rotating, spotted stars. Some analogy with local RS Can Ven binaries seems likely.

Other common classes of objects in the surveys which require further thought include A–F main sequence stars with a scale height near 1 kpc but normal composition; metal poor A–F main sequence stars with an asymmetric drift of about 100 $\mathrm{km \cdot s^{-1}}$; and both globular clusters and halo field stars on counter–rotating orbits, which may differ systematically in age and composition from those on direct orbits.

It is a truism of astronomy that, anytime you open a new window in wavelength or resolution, you will find new phenomena. Preston's talk, reporting on projects that study 10^7 or more stars, made clear that shear numbers of sources can be equally revealing. The talk ended with one of the audience members (Donna Weistrop, U. Nevada, Las Vegas) asking whether the Optical Gravitational Lens Experiment might also have found any gravitational lens events. Since Preston had not actually mentioned these, a break for lunch was clearly in order.

James Higdon (Claremont Colleges) discussed the notorious gamma ray bursters. He and Schmidt were the first to apply the V/V_m method to these in an attempt to learn something about their spatial distribution. Nothing can be said about $N(L)$ for the bursters, since their distances are uncertain over the range from AU to Gpc. But V/V_m or, equivalently, number as a function of apparent flux, brightness, or fluence reveals that they are not uniform in space. In contrast to quasars, concentrated far away, detected gamma ray bursts have V/V_m around 0.3 and are concentrated nearby. Curiously, they are not correspondingly concentrated on the sky toward any obvious structure, like the

Sun, the galactic plane or center, or bright galaxies.

The correct interpretation of this odd pair of properties has been exercising the astrophysical community for several years. Higdon, however, concentrated on the uncertainties of the observational results, suggesting that they are larger than generally recognized, owing to the way data from BATSE are processed and events defined. He believe that, while nearly all the catalogued bursts belong in the sample as defined by the BATSE team, the number of missed and excluded events and the non-randomness of their properties may be an important source of bias in the results. Thus limits on isotropy may not be very tight and the error bars on $V/V_{\rm m}$ could be large. The problem arises because similar events coming from the earth's magnetosphere and the Sun are actually commoner than gamma ray bursts in the usual sense, and events due to the South Atlantic Anomaly and to known astrophysical sources like Cygnus X-1 are not entirely negligible. Higdon also felt that the issue of existence and properties of spectral features in the bursts remains unsettled.

4 Galaxies of Only Marginal Weirdness

Bruce Peterson (Mt. Stromlo and Siding Spring) moved us definitively out of the Milky Way into the realm of the nebulae. He addressed both the difficulties in arriving at a meaningful $N(L)$ and what you learn if you can do so. It remains, perhaps, surprising that nearly all large samples of galaxies can be fit fairly well by what is most often called a Schechter luminosity function. The next most common names (all of which appeared during the three day workshop) are Shechter, Schecter; and Shecter. The confusion apparently comes from cross talk with the name of his sometime co-author, Shectman. Paul (who presumably has no difficulty in himself remembering the correct spellings) has provided the following mnemonic: he has as many extra letters as you can think of to put in; Steve has the fewest possible.

Peterson pointed out that dwarf galaxies are exceedingly common (even here and now) but contribute very little to the luminosity density of the universe or to counts beyond the local supercluster. He believes that definitive results on how the local $N(L)$ has developed from the ones at larger redshift must await still larger data samples, including the Sloan Digital Sky Survey. In the interim, he recommends a normalization of $\psi^* = 1.2 \times 10^{-4}{\rm Mpc}^{-3} \cdot h^{-3}$ and a characteristic bright ness of $M_{\rm j}^* = -19.7$ for Elliptical and SO galaxies and -19.4 for Spirals (or -19.5 for a mixed sample).

The Schechter function with these constants corresponds to a luminosity density in the universe of $1.76 \pm 0.26 \times 10^8 h \cdot L_\odot \cdot {\rm Mpc}^{-3}$, and thus an M/L of $1550 \pm 90h \cdot M_\odot/L$ to close the universe. Since rich clusters of galaxies yield values of M/L in the neighborhood of 300 h, Peterson concluded that we have some evidence for global values of Ω near 0.2.

Bruce Peterson was Schmidt's second doctoral student, and it became clear at this point that five of these six progeny were workshop participants. The sixth, Robert Wilson, sent greetings from the South Pole, where he was observing at the time.

Donna Weistrop (University of Nevada, Las Vegas and student number three) remarked that her thesis with Schmidt had required counting a very large number of faint stars, but that she had since been replaced in that capacity by an APM and would not be presenting any luminosity functions at all. For the galaxies in large voids that she discussed, mere existence is perhaps the most interesting property.

The 31 $h^{-1}\cdot$ Mpc void in the direction of Bootes, about 15000km·s^{-1} from us, contains, at last count, 57 galaxies, including 27 from her sample. Twenty of them are quite faint and associated with brighter galaxies. The total numbers indicate a density inside the void of at most 1/3 the density of galaxies in "average" parts of the universe.

The properties of the galaxies in the Boötes void disagree at some level with virtually every prediction made, thereby, Weistrop pointed out, justifying the existence of observers. Various scenarios of galaxy formation have led various scenarists to say that void galaxies would (*a*) be low mass ones in low mass halos, (*b*) be low surface brightness, giant disk galaxies, or (*c*) include no very luminous or strong emission line ones because the low density would not allow for the mergers and interactions needed to trigger vigorous star formation. In fact, the void galaxies include a full range of luminosities, masses, and surface brightnesses. Some show evidence of interactions, and many have strong Hα and other emission lines, including one apparent Seyfert 1 galaxy. The range of star formation rates implied by the emission lines is roughly $3-55M_{\odot}\cdot\mathrm{yr}^{-1}$, overlapping the range of IRAS galaxies.

Roger Blandford (California Institute of Technology), in the best tradition of organizers picking up dropped balls, substituted for a late-cancelling speaker and addressed the puzzling topic of faint galaxies. He also got what was probably the loudest laugh of the workshop by showing what he said was "the same field in a different color". Close examination revealed that, indeed, the second slide was an image exposed through a different filter, but the dominant impression, caused by the choice of false color imaging for the two pictures, was that the sky was red-orange in one and blue-green in the other.

Apart from the color information ("faint blue galaxies" having become almost a single word), the most striking aspect of the images is the shear number of objects, something like 6×10^5 per square degree, or 20 billion over the whole sky, if you count down to $B=28$ or $K=24$ (as is possible in recent images from the Keck telescope). Blandford believes that these numbers will inevitably increase substantially as we look still fainter and more carefully, though he quoted expert automated photometrist Craig MacKay as saying ,"You can count to 37 if you want to—but don't believe the results".That is, optical astronomers are still in the process of rediscovering a theorem painfully proven by the radio community decades ago: you must not attempt to count more than about one source per 25 beam widths, or you will be confused (in both the usual and technical meanings of the word). At the moment, however, it seems that each magnitude deeper roughly doubles the number of real galactic images.

The large numbers (implying small statistical error bars) provide an enormous temptation to try to do cosmology with the counts. The volume of space at the distances of the faintest galaxies now in the surveys differs by a factor of at least three among otherwise plausible cosmological models. Though the speaker displayed several very elegantly arranged expressions for luminosity distance and available volume as a function of model, redshift, and lookback time, he nevertheless concluded that no particular model was either favored or disfavored by the current counts. The vast majority of the apparently faint galaxies are also absolutely faint. That is , they come from the part of the luminosity function that contributes very little to the total mass and light in the universe. This means that the galaxies can change their properties with redshift in a way that will mimic or conceal any possible cosmological effect without our being able to tell the difference.

Blandford ended by noting that efficient use of large telescope time requires that images resulting from long exposures be used for as many different scientific studies as possible. He showed as an example a 26000 second image of a rich cluster that has already been exploited for faint galaxy counts, study of weak gravitational lensing by the cluster and by larger structures, determination of the two-point correlation function for faint galaxies, and looking for the distortions of shapes of background faint galaxies caused by the gravitational effects of individual foreground galaxies.

Irwin Horowitz (Idaho State University and Schmidt's sixth and most recent PhD student) began the transition to the topic of the next section with a discussion of emission line galaxies (not in voids!). The luminosity function you might find for these depends entirely on your definition of an emission line galaxy and on whether you mean line, continuum, or bolometric luminosity. The Markarian galaxies are the largest sample of the beasts, but the catalogues are neither uniform nor complete and so are not useful for statistical studies.

The underlying energy source for the emission lines in these normal galaxies is necessarily ultraviolet radiation from (mostly) young blue stars. Nevertheless, obscuration effects guarantee that optical emission lines are not very well correlated with the other main signature of rapid star formation, infrared reradiation by dust. Thus, Horowitz concluded, to arrive at a complete sample from which star formation rates and their correlations with other galaxy properties can be derived, it will be necessary for astronomers of the next decade to combine data from IRAS (far infrared), 2MASS (near infrared survey), and optical samples.

5 Active Galaxies, Assorted

Most of us draw a fairly sharp mental line between "normal" galaxies, however bright, in which most of the luminosity comes from stars, and "active" galaxies, in which a significant fraction of the energy production is associated with a massive central black hole. An ancient and still disputed topic is the extent to which the various types (Seyfert and radio galaxies, radio loud and quiet quasi-stellars, BL Lac objects...) can be regarded as fundamentally similar, with a continuum of observed properties controlled by black hole mass, accretion rate, and, especially, the direction from which we observe the fireworks. The claim of lots of similarity is generally discussed under the heading unification, or unified models.

Richard Edelson (University of Iowa, Schmidt's fifth PhD student) began with the relatively mild sort of activity associated with the name of Carl K. Seyfert. He put the Seyfert/quasar cut at $M_B = -23$ (for $H = 50\mathrm{km\cdot s^{-1}\cdot Mpc^{-1}}$, though the speaker did not claim this to be the correct value). Seyferts come in two types (type 1 and type 2, with that remarkable creativity of nomenclature for which astronomers are world renowned). The l's are a bit more so than the 2's, and the unification question here is whether all 2's are really just 1's seen imperfectly through an obscuring torus of stuff (presumably associated with the accretion process) around the central engine.

Though Seyferts are often initially identified optically in what Edelson called "subjective prism surveys", they (like most active types) splash energy all over the electromagnetic spectrum. Thus meaningful luminosity functions, to test whether alignment and obscuration effects can account for the relative proportions of the two types, must use bolometric luminosities. When treated in this way, Seyfert l's and 2's are about equally common, and this provides some additional support for orientation as an important (though not the only) controller of what we see. The existence and numbers of what one might call type 2 quasars (with $M_B > -23$ but only narrow emission lines, most initially found from within the IRAS galaxy sample) similarly indicate an orientation effect.

Patrick Osmer (Ohio State University) moved us on to true quasars, pointing out that it was a 1970 paper by Schmidt that finally persuaded S. Chandrasekhar (then editor of the Astrophysical Journal) that quasar was a well defined word, acceptable for use in polite company. Even as Osmer was recalling this, Schmidt could be heard muttering in the front row that his was really a very vague, data-driven definition. In any case, from that day to this, a countably infinite number of observers have attempted to count quasars as a function of absolute magnitude and redshift. As for most things, faint ones are commoner than bright ones; and, since about 1965, there has been no doubt that all types are commoner at $z \approx 2$ than here and now. This was the first, and perhaps still most spectacular, application by Schmidt of the V/V_{m} method.

Two major astrophysical questions arise. The first is the extent to which quasars (broadly defined) are again less common at $z = 4 - 5$ than at $z \approx 2$. This bears very directly on the epoch at which (at least a few, presumably the most massive) galaxies must have formed. After an early period in which quasar counters discussed the issue at more or less the level of "my survey is more complete than your survey", we all agree that honest catalogues display an $N(z)$ that flattens at $z \geq 3$ and probably turns over. But we see the few, most distant objects through a forest of intervening gas clouds, some clearly associated with galaxies and some of quite uncertain nature. The words "gas and dust" belong together so intimately that we pronounce them almost as one. Thus we can establish a real scarcity of high redshift quasars only after the effects of dust absorption have been allowed for. Bruce Peterson returned to this issue during the discussion, concurring with Osmer that some dust clearly exists and that it is not yet possible to prove it is not responsible for the entire shortage of high redshift quasars (though neither much likes the idea). Favoring the "dust hypothesis" is a sample of very red quasars found by Rachel Webster. Opposing it is at least one radio source sample with complete optical identifications down to quite low fluxes. That is, there are no "empty fields" to correspond to heavily obscured, high redshift quasars.

The second question comes up when you compare quantitatively the luminosity functions, $N(L)$, found at different redshifts. Does the drop in numbers from $z \approx 2$ to $z = 0$ look like each object in a standard shaped $N(L)$ has faded with time (as you would expect if only a few galaxies pass through a quasar phase and take a Hubble time to do it)? Or does it look like the standard $N(L)$ is simply shoved upward at high redshift (as you would expect if most galaxies pass through a quasar phase briefly, more of them doing it early than late)? The former is called luminosity evolution and the latter density evolution. They are indistinguishable for a pure power-law $N(L)$. The real luminosity functions come pretty close to this uninformative shape, but do tend to bend gradually from steeper to flatter power laws at low luminosity. The luminosity at which the bend occurs at different redshifts looks, according to Osmer, perilously like pure luminosity evolution. Most theorists prefer models in which lots of galaxies are briefly active (that is density evolution). Of course, you can always fiddle the detailed history of black hole formation and accretion rates to reproduce the observations with short-lived quasars, but it has a slightly unnatural feel.

Ray Weymann (Observatories of CIW) described the 10% or so of quasars whose spectra are slashed by broad, optically thick (and generally flat-bottomed) absorption lines of Lyman alpha and other common transitions at redshifts very close to their own emission redshifts. These broad absorption line or BAL quasars have been variously regarded as a discrete physical class or as another orientation effect, in which one of a set of clouds with covering factor near 0.1 happens to be along our line of sight. Weyman outlined three classes of models for the clouds, associating them with red giant winds, the accretion disk, or material radiatively accelerated by line locking.

A very important clue is the virtual absence of BAL objects (of which 50 – 60 are known) among radio loud quasars. One complete, radio loud sample of 256 sources has, for instance, no BALs, where 25 or so would be expected. Unfortunately, the Sherlock Holmes who can explain to us the meaning of the "curious incident of the BAL radio quasar" does not seem to have appeared yet. Pinning down the status of these objects is one of the important goals of the HST key project on quasar absorption lines. Weyman believes that the class of "associated" absorption features (meaning those due to gas connected with the source rather than with intervening objects) is probably larger than just the traditional BAL features, but he has no doubts that the majority of absorption lines are indeed intervening material at the distances indicated by the redshifts.

John Bahcall (Institute for Advanced Study) gave us all an uncomfortable moment on the third day by showing results of a recent HST examination of the environs of relatively low redshift quasi-stellars. Since the work of J. Kristian in 1973, we have known that a careful look often reveals the fuzz of a host galaxy, at least for the closest quasars like B264 (examined from the ground by Bahcall, Schmidt, and Gunn at about the same time). HST resolution extends fuzz-mapping capability out to $z = 0.1 - 0.3$. Not all the expected host galaxies were seen. The eight that were had an average luminosity of $M_V = -19.6$; and no hosts are much brighter than L^*.

6 Other Wavelengths

Kenneth Kellermann (National Radio Astronomy Observatory) began with the distinction between radio loud and radio quiet quasars, which goes back to Allan Sandage's 1965 discovery of what he called interlopers, or bright stellar objects. But it is a distinction belonging to the era of relative radio insensitivity. Modern surveys habitually reach the microJansky level, in comparison to 3C, which was complete only to 9 Jy. With the greatly expanded dynamic range, so-called radio quiet quasars quite often turn out to have fluxes in the 10^{24-26}W · Hz^{-1} range, comparable with Fanaroff-Riley type I radio galaxies (FRII's tune in at 10^{26-28}W · Hz^{-1}, and "real" quasars are even louder). That $N(L)$ for quasi-stellars at radio frequencies is bimodal remains true. But the fact that "quiet" does not mean "silent" greatly expands the possibilities for various kinds of unification schemes.

Kellermann claimed that, "like George Preston, I've never won an argument with Maarten", but then went on to describe an issue that is, at least, a draw. When you go to plot a luminosity function for radio sources, should you plot an integral one (N brighter than each L or received flux S), which is Schmidt's preference, or a differential one (N at each L or S), which is Kellermann's preference? In the former case, propagating errors from high flux to low can conceal real information; in the latter case faulty binning can do the same. In either case, the number of sources over the sky has not yet quite reached the GigaGalaxies of optical surveys, but there are about 10^8 to 9 μJy, and the speaker suggested that the supply of 1 μJy radio sources will rival the $m = 27$ optical galaxies, though even at this flux level our poor old Milky Way would make it into the sample only for $z \leq 0.02$. Uncounted sources contribute some false signal to measurements of anisotropies of the microwave background radiation on angular scales near $1'$. The contribution is less than $\Delta T/T = 1.2 \times 10^{-5}$ and will decrease as the surveys improve.

Morphologies as well as numbers of radio sources are a function of redshift. Large doubles, for instance, disappear beyond $z \approx 1$. This makes sense. The lifetime of the radio-emitting electrons against Compton scattering on $3(1+z)K$ photons drops below 10^5 years, and, in the absence of continuous, diffuse acceleration processes, the radio sources must be less than 10^5 LY across, as seen .

Riccardo Giacconi (European Southern Observatory, and much more visible at this workshop than at ones on his home territories over the years) carried luminosity functions onward into X-ray energies. An important long-standing question is whether the X-ray background is really just the sum of discrete sources, and, if so, what those sources are. According to the speaker, 60% of the low energy background (1–2 keV) has been unambiguously resolved into sources in ROSAT data. The dominant contributors are compact sources associated with active galaxies, though the rarer, extended emission coming from galaxies and, especially, clusters is at least as interesting.

As photons and sources have become more numerous, the question of how you identify and characterize these sources in a uniform way across the sky has required increased attention. The speaker is a strong advocate of wavelet transforms as an approach to these problems and also as an aid to data compression (for instance, the storage of the Hubble guide star catalogue on "only " 100 CD-ROMs).

Giacconi's summary of the X-ray cluster situation (disputed by several other participants) was that "Abell did a fantastic job". By this he meant that there is something like 90% agreement between clusters of galaxies as identified by Abell and clusters of galaxies picked out as extended, coherent X-ray sources. It was not clear, however, whether the X-ray data could help to distinguish a single cluster with substructure (and hence more than one X-ray peak) that should be in the catalogue from an accidental superposition of poorer galaxy groups (also with more than one X-ray peak) that should not have been in the catalogue. This would be possible only if $L_{\rm X}/L_{\rm opt}$ were a strong, unique function of cluster richness (clearly not the case). Having a total X-ray luminosity much larger than sum of the individual galaxies is, however, an authentic signature of a real, virialized, collapsed cluster of galaxies.

Douglas Richstone(University of Michigan) described the attempt to derive a luminosity function for "things impossible to see", that is the black holes at the centers of active galaxies, and at least as interesting, at the centers of galaxies that may once have been active but are no longer. Of course, what we really want to know is $N(M)$, and the luminosities of active galaxies provide only a very indirect handle on this via the Eddington luminosity. Such statistical considerations do, however, strongly favor a picture in which many galaxies go through an active phase, leaving moderate to massive black holes ($10^{6-9}M_\odot$) in most L^* galaxies, including, perhaps, our own. AGN counts then require that the mass density in black holes be $0.2 \times 10^6 M_\odot \cdot \mathrm{Mpc}^{-3}$ for a 10% efficiency of conversion of accretion energy into photons (somewhat more if most AGNs are bright in the still under-observed extreme ultraviolet).

Searches for individual black holes require measurements of both velocity dispersion (gas and stars each have their advocates) and surface brightness profile as close as possible to the center of the galaxies concerned. The required angular resolution of better than $1''$ means that HST is already making a dent on the search process, though the use of velocities of water masers in NGC 4258 by a Japanese-American collaboration to establish the presence of a $4 \times 10^7 M_\odot$ black hole strikes one as at least as impressive. Plausible cases for central massive black holes have now been made in half a dozen or so galaxies. Based on these very limited data, the local mass density comes out rather close to $10^6 M_\odot \cdot \mathrm{Mpc}^{-3}$, assuming that the Local Group contribution is dominated by the M31 black hole and Virgo by M87 (a biggy at $2-4 \times 10^9 M_\odot$, according to H. Ford's post-fix HST images and spectra).

7 Largest Scales and the Future

Neta Bahcall (Princeton University) presented luminosity and mass functions for whole clusters of galaxies (she does not entirely agree that Abell did a fantastic job). Curiously, the luminosity distribution over the range $10^{10} - 10^{13.5} L_\odot$ can be fit by the same sort of functional form ("Schechter function")as applies to single galaxies. The corresponding $N(M)$ then also has a characteristic value, which one can call M^* by analogy with L^*. It is about $1.8 \times 10^{14} M_\odot$. Bahcall agreed with Peterson that masses and luminosities of the rich clusters seem to imply a density parameter $\Omega \approx 0.2$, at least out to Mpc scales. Additional consideration of the data, in connection with models for large scale structure, suggest $\Omega\ h$ near 0.2, to be separated as Ω about 0.35 and $h \approx 0.55$. There is probably no inconsistency with $\Omega = 1$, particularly if you want to account for the existence of dynamically unevolved clusters at moderate redshift.

Bahcall touched also on the contentious issues of the two-point correlation functions for galaxies, clusters, quasars and various combinations of them as a function of redshift. She drew attention to the importance of astropsychology, that is, the contribution of what you expect to see to what you do see. The recognition of the importance of gravitational lensing of background QSOs by foreground galaxies and clusters has changed what we expect to see and, apparently, also what we (excluding, as usual, H.C. Arp) do see. She concludes, cautiously, that there are probably no intolerable anomalies in QSO-galaxy associations and that the redshift dependence for galaxies can best be described as "stable clustering".

The last six regular speakers had been asked to consider the future of their several disciplines. Much of what they said, therefore, will be presented more fully when we write up an account of the symposium held in connection with Maarten Schmidt's 75th birthday in 2004–5, and we note here only a few highlights.

Anthony Readhead (California Institute of Technology, on the future of VLBI) called attention to a new class of radio sources, compact doubles that look a lot classical radio galaxies, but are only 100 pc or so across. Not all are superluminal sources.

Joachim Trümper (Max Planck Institute, Garching, on X-ray missions)summarized recent work on X-ray clusters as implying that galaxies make up 2%–7%, gas 10%–30%, and dark matter 65%–85% of a typical 1–2.6$\times10^{15}M_\odot$ cluster in its inner 3 Mpc. He also made dismally clear to American participants the extent to which the future of high energy astrophysics from space is going to be a European, Japanese, and perhaps Russian future.

Richard Green (National Optical Astronomy Observatories. Schmidt's fourth PhD student, on the Gemini project) described the trade-offs needed when you must satisfy observers from at least six countries and as many wavelength (etc.) regimes. The anticipated sub-arc-second resolution will permit, among many other advances, luminosity functions for objects selected much more accurately by morphology.

Donald Schneider (Princeton, Schmidt's third, and second Nebraskan, postdoc, Sloan Digital Sky Survey) pointed out that we ain't seen nothin' yet. While we know that there must be GigaGalaxies per unit sky and 10^8 or more active ones, the number so far catalogued, imaged, or redshifted leaves one feeling a bit like Newton at the seashore. SDSS won't quite record them all, but it will take us out beyond the three mile limit with, for instance, something like complete galaxy imaging in its fields to $z = 0.2$.

Wallace Sargent (California Institute of Technology, Keck Observatory) provided a progress report on the determination of the intergalactic ultraviolet flux that comes from the relative deficit of quasar absorption lines at redshifts very close that of the emission lines ("proximity effect"). He recommends $10^{-21}\mathrm{erg}\cdot\mathrm{s}^{-1}\cdot\mathrm{cm}^{-2}\cdot\mathrm{Hz}^{-1}\cdot\mathrm{sr}^{-1}$ to within a factor of three, anyhow. The question of whether this exceeds what you expect from known uv-bright active galaxies remains open, and,of course, can only be resolved by accurate determination of yet another specialized luminosity function!

The last word belonged to James Gunn (Princeton) who "almost never has an argument with Maarten Schmidt". He surprised many participants by (*a*) suggesting that stars might be at least as interesting as galaxies and quasars,(*b*) casting doubts upon the existence of a well-defined epoch of galaxy formation, in which they suddenly start forming stars and become bright ("Did galaxies turn on?"), (*c*) describing the number of potential galaxies in faint surveys as neither 20 nor 40 billion, but rather infinite, with detectability so strong a function of gas content and star formation rate that modeling of "evolution" might not be very meaningful, and (*d*) relegating the very largest redshift quasars to the realm of the uninformative, at least in comparison with filling in our knowledge of objects near the peak of $N(z)$, yet another of the goals of the SDSS.

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