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Spiral Galaxies on the Chess Board

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1. Introduction

Last summer I published a Letter in the scientific journal *Nature* in which evidence was presented for a relatively high content of obscuring dust in spiral galaxies. This work, together with a more detailed analysis of the properties of the light absorbing bodies (ESO preprint 730) and a study of the rotation curves of some dusty spiral galaxies with González-Serrano (ESO preprint 731) was high-lighted in an ESO press release (PR 07/90 No "Missing Mass" in Opaque Spiral Galaxies?). Here, I will address some comments and frequently asked questions related to this work.

The new analysis of the dust content of spiral galaxies is based on data from *The Surface Photometry Catalogue of the ESO-Uppsala Galaxies* (by Lauberts and myself, in short ESO-LV), a project which was described in the *Messenger* (LV 1983, 1989). In the Introduction to this catalogue, which contains about 180 parameters for 16,000 galaxies, an extensive discussion is given of the photometric accuracy (thought to be better than 0.15^m in surface brightness) and the completeness and selection effects of this galaxy sample and its various subsamples. Today, after two years of intense research on this data base, it is a great pleasure to say that only a very minor amount of errors have been found so far and I would like to use this opportunity to express my deep appreciation for the enormous dedication of my co-author Dr. Andris Lauberts, who worked full-time on this project for so many years.

The basic idea to study the dust content and hence the degree of transparency in spiral galaxies by means of photometric data is very simple. We think of spirals as flattened round disks that contain dust and stars. Stars emit light; dust particles absorb and scatter light (together called "extinction"). When such a disk is seen from the top it appears round and we see the integrated star light attenuated by the dust along the line of sight. When we see the same disk at a tilted viewing angle, the line of sight will have a larger path-length through the disk, hence it will meet more stars, but also more dust. The tilt angle of the intrinsically round disk can be deduced from its observed axial ratio a/b.

The basic steps to study the transparency are then: (i) to select a *sample* of spiral disks with supposedly similar intrinsic properties, (ii) to make *models* of the spatial distribution of both the dust and the stars in a disk, (iii) to make an analytical solution for these models, describing how for a certain dust content, various *photometric parameters* are expected to change with viewing angle or *a/b* and, eventually, (iv) to fit these models to the photometric parameters of the sample galaxies.

Although, in theory, these steps appear rather simple and straightforward, in practice the choice of samples and its effect on the other steps is quite delicate. The discussion in the literature is extensive and complicated, not only by the different photometric parameters used for the analysis, but also by the wildly different properties of the different sub-samples used. Table 1 summarizes a few of the most popular photometric parameters used (horizontal direction) while, vertically, different employed sub-samples are listed. Basically, each of the 64 boxes in the table can provide information on the effective transparency, but for each box one has to evaluate the *intrinsic distribution* of the particular parameter used and its relation to the observed distribution, both as a result of *selection effects* and effects of incompleteness. The selection effects are so much dependent on both the type of parameters used and on the selection criterion employed, that each box constitutes its own story. Most selection effects are distance dependent and the degree of complication is further quadrupled when the particular parameter used for the test is in itself distance dependent. In Table 1 distance dependent parameters and sample cuts have been shaded, high-lighting the 'doubly difficult' boxes.

Related to the distance dependent selection effects is the so-called Malmquist bias, an effect that puts categories of objects into a sample even while their average intrinsic parameter value would have prohibited them to pass the selection criterion. This is because of the dispersion around that average value, either due to a cosmic dispersion or due to measurement errors. Since there exist more faint than bright galaxies, the Malmquist bias has some amplification and lets more faint galaxies enter a sample than bright ones drop out. A similar effect is well known in radio astronomy, when counting radio sources close to the noise level of the observations.

To complicate matters even further, one has to care about the possible presence of spheroidal bulges that off-set the assumption of disky objects. Fortunately, the effect of bulges can be shown to be very minor for Spirals of type ≥3 (Sb, Sc, Sd). This has also

TABLE 1: *The 'chess board' of selected samples and parameters for transparency studies*

	Diameters		Magnitude	Surface brightness			Axial ratio	Dia. ratio
SAMPLES	D_e	D_{26}	B	μ^{proj}	μ_0	μ_e	a/b	D_{26}/D_e
Magnitude: B < 14.5	–	De Vauc.-Fig. 1a	–	Holmberg	–	–	–	–
Diameter: D_{26} > 80″	–	–	–	Holmberg	–	–	Spiro	–
Diameter: D_{26} > 60″	–	–	–	–	•	• Fig. 2	–	•
Surface brightness	–	–	•	–	–	–	–	–
Volume: < cz <, B	–	Choloniewski	–	–	–	–	–	–
Volume: < cz <, D_{26}	–	Burstein, L	•	–	–	–	–	–
Volume: < cz <, μ_0	–	Fig. 1b	–	–	–	–	–	–
Volume: V/V_{max}	–	Fig. 1c	–	–	–	–	–	–

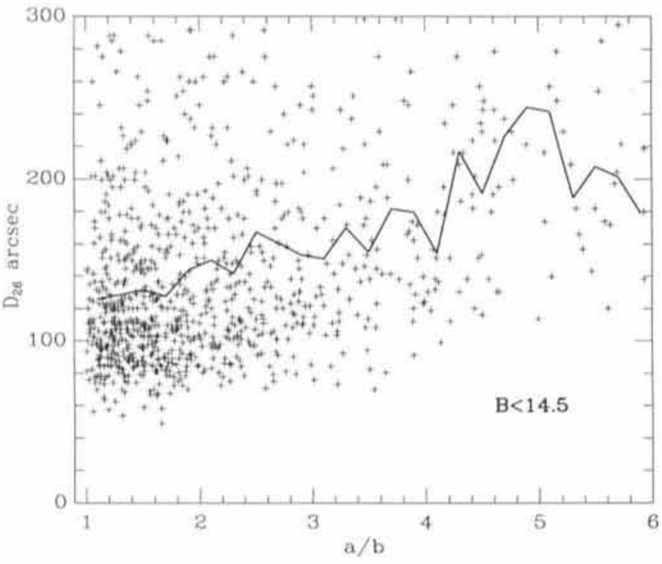
• Key-tests on ESO-LV data presented in the *Nature* paper.

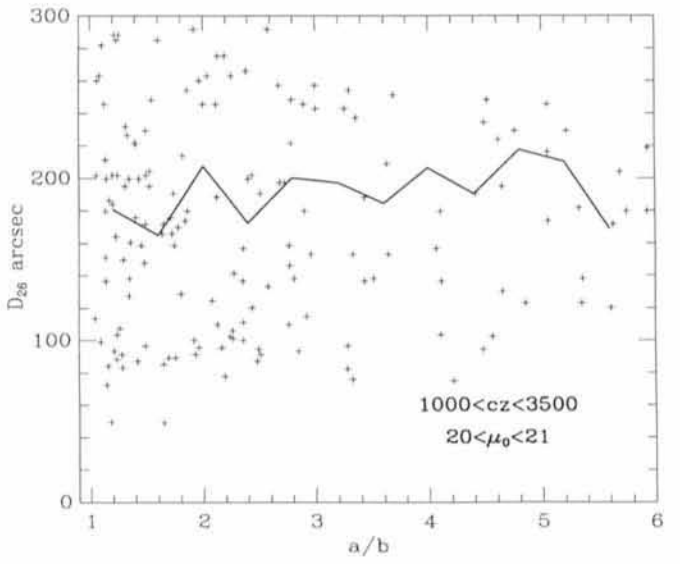
been confirmed, amongst others, by a recent compilation (also using Kent's data) presented by Simien (Observatoire de Lyon) at an ESO seminar.

2. The Analysis in Various Boxes (Sample, Parameter)

The ESO-LV data can be used and have been used for analyzing the effective transparency in almost all of the boxes in Table 1, since each of the photometric parameters (including the intensity weighted axial ratio *a/b*) have been determined by the computer programmes. Especially, the homogeneous acquisition of the data allows a very detailed evaluation of the selection effects involved. But, a paper that would describe all this, including a full analysis of each box would become rather unreadable. After all, one would be tempted to discuss the result of one box in comparison with that of another and eventually the degree of complication might remind us of the chess-board.

How tricky the selection effects can be is illustrated by the test in the box ($B<14.5^m$, D_{26}). When isophotal diameters of a magnitude selected sample are





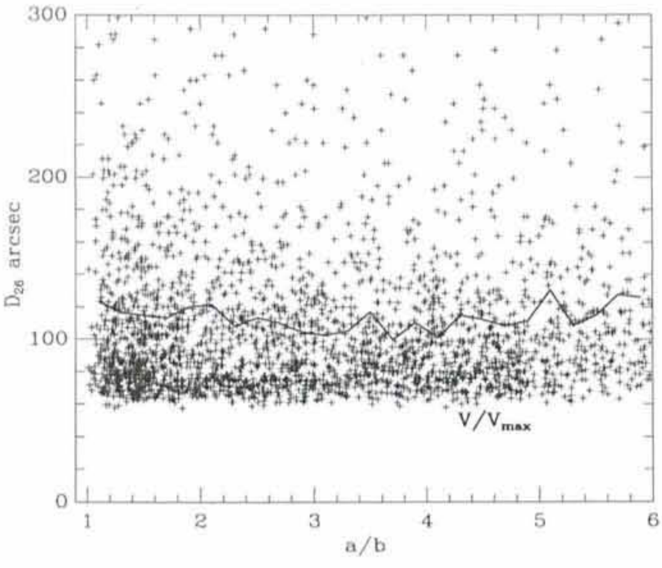


Figure 1: *The isophotal diameter at the Blue 26th isophote of ESO-LV Sb galaxies versus axial ratio a/b for three different subsamples drawn from the same parent sample. Magnitude limited (upper left), redshift limited (upper right) and V/V_{max} limited (lower left). While the average regression with a/b (line) for the magnitude limited sample indicates fully transparent galaxies, the other two, more proper spatial volume representative samples, indicate extremely dusty conditions.*

plotted versus *a/b*, a clear increase (~45%) with increasing *a/b* (1 to 5) can be noted – see Figure 1a. In fact, this is also the case for diameter selected samples. The amplitude of this increase conforms to the expectation of fully dust free – i.e. *transparent* – galaxies and such data provided the motivation for adopting fully transparent models for the outer regions of spirals in numerous papers (e.g. de Vaucouleurs, RC2). But this box represents one of the doubly distant dependent cases, where all distance dependent selection effects cooperate. When a subset of the same sample is taken for which redshifts have been measured, and subsequently only a particular *volume* of space is used in which galaxies have been selected in a more representative way (galaxies with radial velocities cz<3500 km/sec and limited range of central surface brightness, μ_0) the increase of the diameters is reduced to 9%. But the redshifts have been measured for only a limited number of not necessarily randomly chosen objects. An alternative way – not using redshifts – to construct spatial volume representative samples is provided by the application of the V/V_{max} test, which is detailed in the Introduction to ESO-LV. The last panel of Figure 1 shows that the diameter increase with *a/b* virtually disappears for such a V/V_{max} complete subsample of 2047 galaxies, and is now consistent with *fully opaque* models for the outer regions of spiral galaxies. The V/V_{max} sample deserves a more extensive discussion, but this example demonstrates how the distance dependent selection effects can conspire to mimic transparent systems and how dangerous it is to draw conclusions from 'doubly difficult' boxes. In a paper in press in *Monthly Notices*, Chołoniewski (Warsaw) concludes from a different galaxy sample (CfA), for which redshifts have been obtained in a complete fashion, that isophotal diameters do not increase with *a/b*, confirming an earlier suggestion by Burstein and Lebofsky (1986). The example of the isophotal diameter test demonstrates how critical the definition of the sample is for the type of result one obtains.

In the *Nature* paper, I outlined that the classical test (box $B<14.5^m$, μ^{proj}) presented by Holmberg, which highly influenced the view that spiral galaxies are transparent, could be equally well interpreted with simple fully opaque galaxy models. Similar worries have been raised by Disney et al. (1989). The basic reason for this ambiguity was the definition of the average projected surface brightness μ^{proj}, which was such that its regression with *a/b* does not discriminate between different models. Holmberg most clearly described what he did, but for some (unclear) reason his results later propagated in the literature as *evidence* that spiral galaxies are essentially transparent.

Now, if both the 'classical techniques' that formerly led to the notion of transparent spiral galaxies are ambiguous, how can we proceed without introducing similar ambiguities? The key to this problem is the availability of actually measured surface brightness profiles in ESO-LV. In itself surface brightness (s.b.) is a *distance independent* parameter, which leaves only the worry about distance dependent selection effects in the sample definition itself. When verifying the axial ratio distribution of the samples used with the expected distribution of randomly projected axial ratios and by carefully screening the results with the diameter selection procedure, it is possible to perform a complete, unambiguous analysis of the problem. However, this is greatly due to the fact that the ESO-LV data can give us a rather good description of the *input* (i.e. cosmic) distribution of the s.b. of the target galaxies. The amazingly small spread of 0.6^m of the central s.b. (Freeman, 1970) has been confirmed (average 21–22 mag/arcsec^2), albeit with the refinement that it becomes fainter for later type galaxies. That this in itself is *not* a result of distance dependent selection effects, could be demonstrated by computing the average central s.b. of the V/V_{max} samples, which are supposedly representative for particular volumes of space. The average central s.b. from the V/V_{max} samples agreed within 0.25^m with that of the total samples, which confirms the results of van der Kruit (1976). Davies et al. (priv. comm.) recently pointed out that if, conversely, the narrow range of observed s.b. was caused by selection effects, then the s.b. tests would be more ambivalent. This might be partly true in theory, but the ESO-LV data appear to constrain the cosmic distribution of s.b. to an amazingly narrow range, which greatly facilitates its application to studying transparencies.

In Figure 2 the s.b. at the half total light radii are plotted versus *a/b* for Sb and Sd systems. While the regression with *a/b* for the Sd's conforms to simple semi-transparent models (C=0.5), the data of the Sb's are consistent with opaque models, i.e. s.b. hardly decreasing with *a/b*. Also, in the central parts the s.b. does not appear to depend on *a/b*, but the greatest surprise to most of us was the result at the half total light radius, which seems to indicate that large parts of the disks of spiral galaxies are very obscured by dust. This result

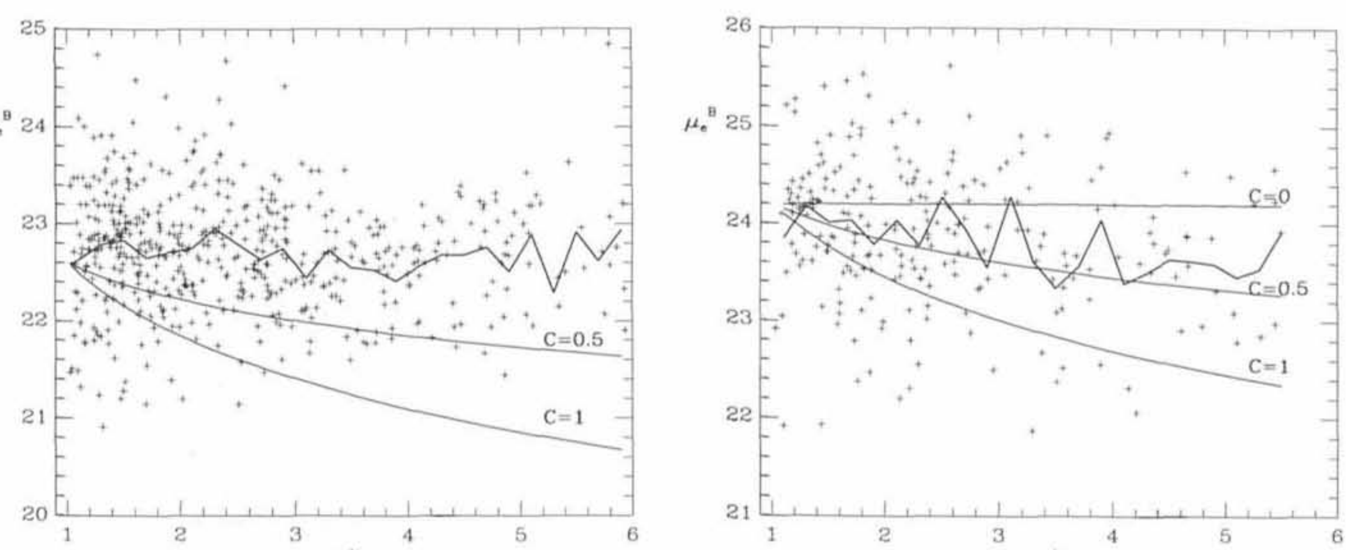


Figure 2: *The local surface brightness at the effective radius of ESO-LV galaxies that exhibit a pure exponential luminosity profile (N ~ 1) on both the Blue and the Red plates. These galaxies are thought not to contain any significant bulge component. The left panel shows the very small decrease of the s.b. with a/b of ~Sb galaxies-conform very dusty scenarios –, while the right panel shows similar data for apparently much more transparent, very late type spirals (type > 7.5, ~Sd's). The curves correspond to simple fully transparent (C=1) and semi-transparent (C=0.5) models.*

could be further extended to the outer regions of the disks by analysing the distance independent ratio D_{26}/D_e *and* by several tests that operated on the total magnitudes.

In the *Nature* paper I argued that these results are most consistent with the view that spiral galaxies are opaque over large parts of their disks. While Burstein (1990) apparently agrees with these conclusions, he wonders whether attention had been given to the effects caused by the sample definitions (without discussing the actual work presented on this). Well, as a matter of fact, this was what most of the work was about. In Figure 2 of the *Nature* paper it was demonstrated that the prime selection effect that operates in a diameter selected sample could be only understood in terms of opaque spiral disks, while that same basic selection criterion would lead to a serious inconsistency in the case of transparent systems.

So, in other words: by carefully evaluating *how* galaxies were selected, it could be shown that the result of that selection procedure could be best understood in terms of opaque systems. In addition, a *control* sample was designed for the brightest galaxies, to evaluate any remaining distance dependent selection effects. The *a/b* distribution of this control sample is representative for a random projection of axial ratios and reproduced the results of the total sample. Indeed, it is not *a priori* the large size of the ESO-LV sample that permitted to obtain the new results, it is merely the very strict selection and homogeneous acquisition in combination with the possibility to create various sorts of smaller subsamples (types, s.b. redshift, etc.) to perform a variety of verifications.

At a session at CERN, Spiro (CEN-Saclay) presented some of his findings in the box ($D_{26}>80''$, *a/b*), which refers to studying the *frequency* distribution of axial ratios. This is one of the 'doubly difficult' boxes since, although axial ratio is principally distance independent, it is subject to a Malmquist-like distance dependent selection effect, which operates as follows: Sb-c galaxies with transparencies as indicated by the s.b. tests will undergo an increase of the isophotal diameter by about 9% when seen with an *a/b* of 5. This implies that around the diameter cut-off limit, highly inclined objects will enter a diameter limited sample in some cases even while their face-on diameters would have prohibited that. The fact that there are *more* fainter (smaller) galaxies than brighter ones strongly amplifies this effect, which was ignored by Spiro when he concluded that the noted excess of high *a/b* galaxies must result from intrinsically transparent systems. In fact, by analysing the $D_{26}>80''$ sample, the same effect that has been described in the *Nature* paper at fainter magnitudes for the $D_{26}>60''$ sample has been transferred to brighter galaxies. No wonder that I dedicated this article to the chess board! In fact, if Spiro had inspected a control sample with central s.b.<20.5, he would have noted that the excess of high axial ratios is entirely eliminated, which cannot be explained by his 'transparent model', but is well understood in the descriptions I gave.

This example again illustrates how dangerous it is to embark on double difficult boxes, and that one can then obtain results that look clean and good, but are dictated by selection effects, as with the data presented in Figure 1a. Using the frequency distribution of axial ratios to directly deduce transparencies can only be done when one knows *a priori* the luminosity function of the galaxies studied. In my work I used the frequency distribution only as a check on the representative nature of samples.

At a session of the Dutch Astronomers Club, van Albada questioned whether the effect of the physical thickness of disks could influence the results of the s.b. test as shown in Figure 2. While my studies of axial ratio frequency distributions indicated that the effect of the disk thickness is only evident at *a/b*>5, he suggested that this might already be the case at *a/b*>2–2.5 and he presented results of fits to the small range of *a/b*<2–2.5, which essentially represent face-on systems. In spite of the fact that the increase of the line of sight with axial ratio goes linearly with *a/b*, he presents the data versus *b/a*, which masks the very strong degradation of the resolution of the the test when cutting off the sample at *a/b* =2–2.5. By applying detailed axial ratio deprojection algorithms, it could be deduced that the spiral structure of our target galaxies causes the intrinsic face-on axial ratio distribution to peak at *a/b* ~1.4. So, in practice the fits presented by van Albada correspond to *a/b* =1.4:2–2.5 or a nominal 43–70% increase of the line of sight, opposed to the fits presented in my work *a/b* =1.4--5 corresponding to 257%. This implies that they degraded the resolution of the test by a factor of about 6–4 and not surprisingly, the data are then less conclusive and could represent semi-transparent situations.

Anyway, a more elegant way to assess the effect of the disk physical thickness is by comparing the results of other parameters that are supposedly much less affected (like total magnitudes and the mean s.b. within the effective radius) with those of 'suspected' parameters. Both the tests using total magnitudes and especially the s.b. test using the the mean surface brightness within the effective radius, reproduced the results of the tests using local s.b. values, demonstrating that it is quite unlikely that the disk thickness is affecting the outcome of the tests for *a/b*<5.

3. Opaque, Optically Thick, $\tau>1$, $\tau>>1$

The observed dependency of the s.b. on *a/b* could be well fitted with simple models of single layers of light emitting stars mixed with light absorbing bodies, which can either represent scattered dust particles (cirrus) or compact opaque clouds. For Sb and Sc galaxies these layers are then found to have, *on average*, a face-on optical depth τ (i.e. ratio between disk metric thickness and mean free path of a photon) of, respectively, 2 and 1.3 for the outer parts and higher values for the central parts. Since these values do not include the effects of scattering and a possible small contribution of fully transparent layers on top of the disks, they represent lower limits. This means that on average we miss *at least* half of the emitted light when a galaxy is face-on and that values of $\tau>5$ must be common for inclined galaxies with *a/b*~2.5. In this regime of optical depth, the photometric properties of spiral galaxies are entirely like opaque systems, which is the basic justification to call them opaque as opposed to transparent or even semi-transparent.

On the other hand, the term is slightly confusing since it does not discriminate between $\tau=2-5$ and $\tau>>1$. We simply miss the vocabulary to separate $\tau>1$ and $\tau>>1$. Although, both in the central areas and along the spiral arms most likely $\tau>>1$ and even in the inter-spiral arm region of nominally inclined spirals the data indicate $\tau=5$, both implying that we are essentially seeing stars from the front side, we must remember that we are here discussing average properties integrated over large parts of these systems. The deduced range of τ can very well allow us to see through the disks occasionally; for instance a typical face-on $\tau=2$ can imply that we can detect on average about half of the quasars behind such a disk when the obscuring material is composed out of compact molecular clouds, or see them attenuated by 1 magnitude, when the dust is in the form of well-distributed cirrus.

Both predictions are in practice very difficult to verify. The big geometrical difference between these two examples illustrates the probably most dramatic aspect of the results. Our interpretation of observational data will heavily depend on the spatial structure of the light absorbing components, and much more refined models than those applied in the tests should be constructed. The simple models used in the test serve to provide some first constraints. How complicated the real situation might be is illustrated by a recent paper by Dickman et al., 1990, in which the spatial structures of some molecular cloud complexes were proposed to be best described by fractals! I for one will be reading with great interest any future papers on this subject.

4. Why Relating to Dark Matter?

The notion of the 'missing mass' in spiral galaxies originates from a comparison of the rotational velocities with the amount of observed light and its spatial distribution. If studies of transparency indicate a drastic re-interpretation of the detected light, then it seems natural to reflect how that would affect such missing mass analyses. Recently, Davies (1990) published a paper anticipating $\tau >> 1$ in the central parts of spiral galaxies, which, as he argued, could lead to a dramatic underestimate of the amount of stellar matter in the bulges of spirals. By accordingly increasing the contribution of the bulges, he computed flat rotation curves, which did not require any additional missing mass. However, as Simien pointed out, $\tau >> 1$ in combination with heavy bulges would inevitably lead to an asymmetric light distribution of such bulges, when the disks are seen under a tilted angle. Such an asymmetry has never been observed and, as he says, would have been noted in the detailed bulge to disk decompositions performed for large numbers of galaxies. Note, that for $\tau = 2$ disks this asymmetry would be much less dramatic.

My own results seem to indicate that at least half of the star light of face-on galaxies is obscured by dust, implying that the true luminosities are at least a factor of two higher. Consequently, the mass-to-light ratios *M/L* of the stellar populations that resulted from the 'missing mass analyses' should be divided by at least a factor of two. The point is, however, that the 'missing mass' analyses that incorporated haloes of dark matter already resulted in quite low *maximum M/L* ratios for the material in the disks. Moreover, most of the studied objects are inclined, which facilitated the mapping of the velocity field. When the new extinction results are applied to the luminosities of these disks the resultant *M/L* values drop well below 1 for almost all cases, which values are significantly lower than found in well studied stellar populations. In other words, the current disk-halo solutions combine an *overluminous* disk with an *underluminous* dark component, and become less credible. This fact, together with the suggestion from the absorption studies that the absorbing medium is more widely distributed over the disks than the stars (implying that the observed M/L decreases with radius from the centre) simply calls into question the evidence for dark haloes, as inferred from a comparison with optical light profiles.

This triggered I. González and myself to compute a new category of mass models, now without dark haloes, to fit the observed rotation curves. Indeed, we could find good fits to the rotation curves, but a substantial fraction of the mass that was labeled as discrepant in previous studies, should now be identified with the obscuring component itself! This has been often misquoted in the press, where it was wrongly said that all the discrepant mass was found to be in the obscured prime stellar component with the same spatial distribution as the observed radial luminosity profile. It can be shown in several ways that such a solution would not work and would not resolve the mass discrepancy at larger radii. To our surprise, we found that if the obscuring component was composed of compact molecular clouds, that they would precisely have the correct mass as required by the fits and at the same time perform the amount of absorption required by the optical extinction studies.

Is this implying that the dark mass in spiral galaxies has been found? The extinction results certainly weaken the evidence for dark haloes, and they directly point to the presence of a baryonic component that has the correct spatial distribution to resolve the discrepancy. But can the agreement with molecular cloud mass be circumstantial? Yes it could, and this suggestion needs verification.

On the other hand, an evaluation of the situation in the Galaxy seems not to contradict this suggestion; recently, a number of papers showed that the CO luminosity $-H_2$ mass conversion factor, on which most of our understanding of the molecular mass is based, might be a factor 4 larger in the outer regions. Apart from a few very nearby galaxies, we can only guess the conversion factor in external galaxies. Next to this, several reports reveal a factor 4 higher virial mass of molecular clouds than deduced from the CO luminosities. It also remains to be seen how many molecular clouds are hidden in the noise of the observations. One team of observers that already observed a quite high spatial density of molecular clouds claim that the deflection of the noise distribution of their observations indicates that 68% of their signal is below their detection limit (Lee et al., 1990).

The final word has certainly not yet been said and the current results only form a starting point. The great number of very interesting studies of molecular gas that are presently conducted at many observatories might shed some light on these very cold and dusty regions of the universe. Or, do we have to wait for the launch of the Infrared Space Observatory in 1993, when new windows will be opened that will allow the attempt to detect some lines of the H_2 molecule?

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