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Dust radiative transfer: modeling the complex interplay between dust and starlight in galaxies

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Interstellar dust grains efficiently absorb and scatter UV and optical radiation in galaxies and therefore can significantly affect the apparent structure of spiral galaxies. We have developed and used the 3D Monte Carlo code SKIRT to investigate the complex interplay between starlight and dust grains in galaxies. We investigate the effects of dust attenuation on the observed structural properties of bulges and discs, and find that the effects of the dust are strongly affecting the bulge structural parameters. In particular, dust effects can lead to underestimation of the bulge-to-disc ratio up to a factor of 2 in the V band, even at face-on orientations. We present the first results of the FitSKIRT code, a tool designed to fit detailed radiative transfer models to optical/NIR images of dusty galaxies. Oligochromatic fits to a sample of 12 edge-on spirals from the CALIFA survey mainly confirm that the dust in spirals is distributed in a thin and radially extended disc, with face-on V-band optical depths up to 2. Finally, we combine FitSKIRT radiative transfer models with *Herschel* observations to investigate the dust energy balance in nearby edge-on spiral galaxies. We find a clear inconsistency in the dust energy balance: the amount of dust needed to explain the dust lane morphology in optical/NIR images is several factors smaller than the dust seen in emission in FIR/submm maps. The most likely explanation for this energy balance problem is that a sizable fraction of the FIR/submm emission arises from additional dust that has a negligible extinction on the bulk of the starlight.

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1. Introduction

Dust grains play a special role in producing and processing radiation. They are efficient at absorbing and scattering UV through NIR photons and then reradiating the absorbed energy in the infrared and submm wavelength range. Understanding the intrinsic properties of dusty galaxies, including the dust itself, therefore requires 3D dust radiative transfer calculations. Unfortunately, the 3D dust radiative transfer problem is nonlocal and nonlinear, which makes it one of the hardest challenges in computational astrophysics [1]. SKIRT [2, 3] is an efficient 3D non-LTE Monte Carlo radiative transfer code designed to treat radiative transfer problems in dusty systems. It offers a full treatment of absorption, multiple anisotropic scattering and thermal LTE and non-LTE dust emission, and is equipped with a range of hierarchical and unstructured grid structures that allow the user to handle any 3D geometry without limitation [4, 5, 6]. It is highly optimized using standard and novel Monte Carlo optimization techniques [1].

2. Dust and the apparent properties of galaxies

It is well-known that the presence of dust influences the apparent structural parameters of galaxies, such as apparent scale lengths, surface brightnesses, axial ratios, etc. Several authors have investigated these effects using radiative transfer modeling with varying degrees of sophistication and/or geometrical realism. We have investigated the systematic effects of dust attenuation on the apparent detailed structural properties of discs and bulges simultaneously [7]. We have created artificial galaxy images, using SKIRT radiative transfer simulations, to mimic the observed structural properties of disc galaxies with classical and so-called pseudo-bulges (i.e. disk-like bulges), and include the effects of dust attenuation in the observed light distribution. We find that the effects of dust on the structural parameters of bulges and discs obtained from 2D bulge/disc decomposition cannot be simply evaluated by putting together the effects of dust on the properties of bulges and discs treated separately. In particular, the effects of dust in galaxies hosting pseudo-bulges might be different from those in galaxies hosting classical bulges, even if their dust content is identical. We find that the apparent size and density profile of bulges can be severely affected, and that the apparent attenuation of the integrated disc light is underestimated, whereas the corresponding attenuation of bulge light is overestimated. Dust effects are more significant for the bulge parameters and, combined, they lead to a strong underestimation of the bulge-to-disc ratio, which can reach a factor of 2 in the V band, even at relatively low galaxy inclinations and dust opacities (see Fig. 1).

3. Radiative transfer fits to edge-on spiral galaxies

The most direct method to trace the dust grains in galaxies is to measure the thermal emission of the dust grains at FIR/submm. A crucial limitation, particularly if we want to determine the detailed distribution of the dust in galaxies rather than just total dust mass, is the poor spatial resolution of the available FIR/submm instruments. The 3D dust distribution in galaxies can be determined by the extinction effects of the dust grains on the stellar emission in the optical window, i.e. by radiative transfer modeling. Radiative transfer fitting of individual galaxies requires the combination of a radiative transfer code and an optimization procedure to constrain the input

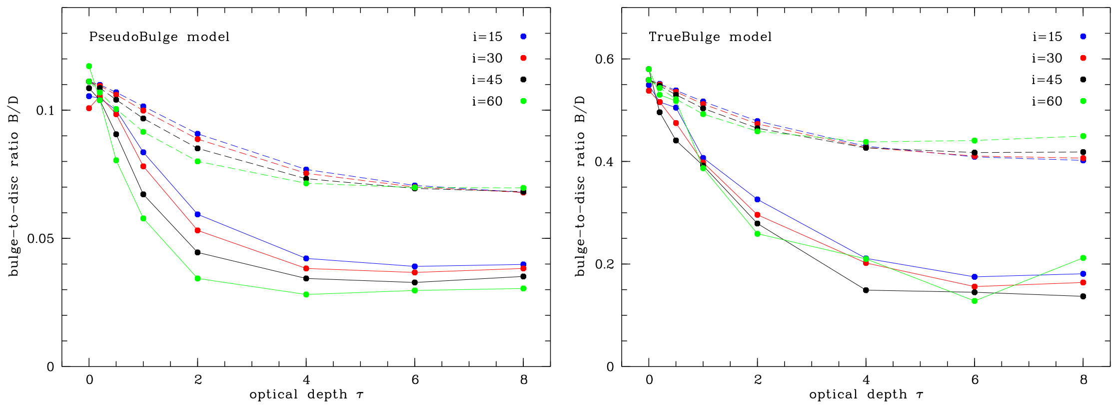

Figure 1: Dependence of the bulge-to-disc ratio on the V-band optical depth. The solid lines represent the apparent bulge-to-disc ratio as derived from a bulge/disc decompositions of the dust-affected images. The dashed lines represent the actual bulge-to-disc ratio [7].

parameters. All too often, this optimization procedure is neglected and chi-by-eye models are presented as reasonable alternatives. FitSKIRT [8] is a genetic algorithm based method designed to efficiently fit radiative transfer models to UV/optical images of dusty galaxies. The most recent *oligochromatic* version of the code allows the user to simultaneously fit a single 3D galaxy model to multiple images in different bands [9].

We have applied FitSKIRT to *griz*-band images of a sample of 12 edge-on spiral galaxies selected from the CALIFA survey. Edge-on spiral galaxies are an ideal target class for radiative transfer modeling: the dust in these systems shows prominently as dust lanes in optical images and they are the only systems that enable a direct view on their vertical structure. In general, the results of the fits are amazingly accurate, given that the fitting was done by an automated procedure over a large parameters space without strong boundary conditions. In the *r* and *i* bands, more than half of the pixels have a deviation between observed and model surface brightness of 15% or better. Our results, largely in agreement with previous radiative transfer modeling of edge-on spirals [10, 11], indicate that the dust is distributed in a thin and radially extended disc. The V-band face-on optical depth of the dust varies between 0.2 and 2, indicating that spiral galaxies are largely transparent at optical wavelengths [9].

A self-consistent treatment of extinction and thermal emission, i.e. a study of the dust energy balance, gives the strongest constraints on the dust content of spiral galaxies. This can be done by combining FitSKIRT fits to optical/NIR images and *Herschel* and other mid- and far-infrared data. The first galaxies we have investigated are UGC 4754 [12], NGC 4565 [13], and M104 [14], and we are now enlarging the sample using edge-on spiral galaxies from the H-ATLAS [15] and HEROES [16] surveys. In all cases, we find a clear inconsistency in the dust energy balance: the amount of dust needed to explain the dust lane morphology in optical/NIR images is several factors smaller than the dust seen in emission in FIR/submm maps. An apparently straightforward explanation might seem that the standard FIR emissivity is actually underestimated by a factor two to three. This possibility is, however, ruled out by our observations [12]. Instead, we argue that the most likely explanation for this energy balance problem is that a sizable fraction of the FIR/submm emission arises from additional dust that has a negligible extinction on the bulk of the starlight.

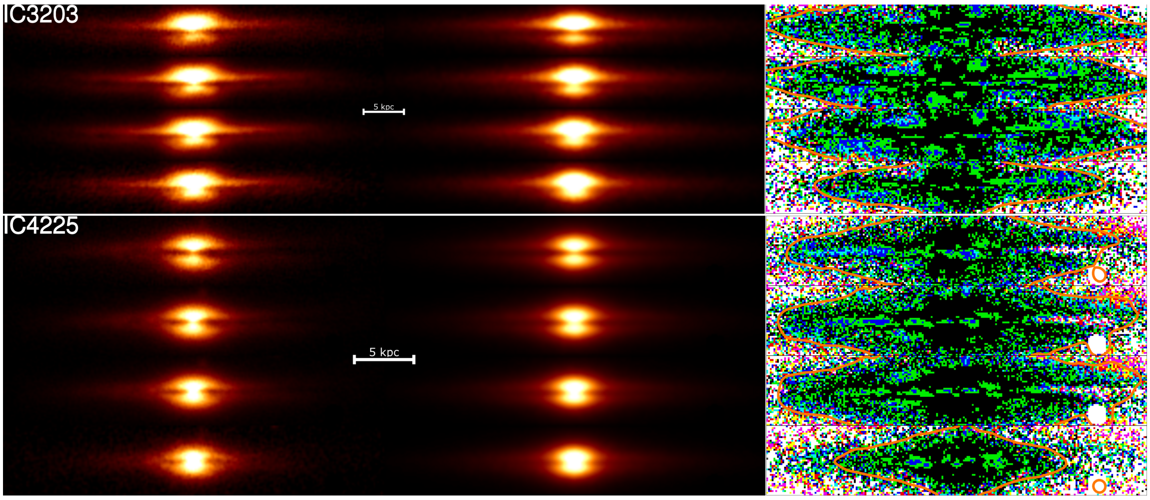

Figure 2: Oligochromatic FitSKIRT radiative transfer fits to 2 edge-on spiral galaxies. The left-hand column represents the observed images in the *griz* bands, the middle column contains the corresponding fits in the same bands, and the right-hand column contains the residual images [9].

The most likely candidate would be young stars deeply embedded in dusty molecular clouds. The compact dust clumps can boost the FIR/submm emission of the dust, while keeping the large-scale extinction relatively unaltered [12, 14].

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