The Spectral Energy Distribution of Galaxies
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Conference Summary

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1. ISM & the Emergent Light from Galaxies

If galaxies consisted only of stars, and some early-type systems in general and dwarf spheroidal galaxies in particular fit this prescription, then the calculation of the SED in principle is straightforward. The emergent luminosity at any wavelength simply is the sum over all the luminosities of all the stars in the system. This can be calculated, of course provided that one has a complete understanding of stellar populations, which remains a non-trivial issue. Most galaxies, however, also contain an interstellar medium (ISM). The ISM absorbs, scatters and reprocesses the radiation and relativistic particles from sources within galaxies, primarily stars and AGN. That the ISM is neither isotropic nor homogeneous adds to the challenge of how to properly account for its influence on the luminosity emerging from galaxies.

Light interactions within the ISM naturally vary with wavelength. For example in the Lyman continuum, absorption via bound-free transitions of H and He are extremely important and give rise to strong emission lines in the ultraviolet and especially the optical to near-infrared regions. The presence of especially H-recombination lines offers a key window into the numbers of short-lived O-stars and thus galactic star formation rates. They also affect colours of galaxies and therefore need to be incorporated in stellar population models. While we see that this is done in modern models, the issue remains as to what is the best prescription for the inclusion of emission line features and how this should vary with host galaxy properties.

Interstellar dust is a critical factor in spectra from the mid-UV to near-IR, where it absorbs and scatters light, with absorbed energy being re-radiated into the thermal infrared-millimeter regime. The most basic approach is to deal with the balance between absorbed and reradiated luminosity components with a correction for scattering. Dust scattering is problematic because it involves a phase function that can perturb the angular distribution of the radiated light. For example, forward scattering by dust can enhance the intensity of light scattering out in the polar direction from a disk starburst with a bipolar wind, as in an M82-type of situation. Polarization thus remains an important diagnostic for assessing the importance of scattered light in galaxies.

The effects of dust naturally are nonlinear, $I = I_0 \mathrm{e}^{-\tau}$. As each sightline through a galaxy has its unique τ_i, even the case of a galaxy where the ISM is assumed to have uniform properties is complicated. The choice of the mean obscuration to each point on the projected image of a galaxy, $\overline{\tau(x, y)}$, is not readily obtained from observations. The exceptions are cases where discreet objects can be studied, e.g., stars or star clusters, in which dust obscuration maps in principle can be obtained. Comparisons of these types of maps with results based on the more traditional integrated light methods is offering important tests of our current models.

Of course in real galaxies dust properties, e.g. column densities and compositions, also can substantially vary with location. This behaviour occurs in the Milky Way, as well as being seen between different types of galaxies. We therefore have seen the considerable effort devoted to empirically assessing variations in dust properties through measurements of the influence of dust on emergent spectra, as, for example, in the "Calzetti (*et al.*) law" approach to estimating ultraviolet dust obscuration.

While we have seen progress in this area, dealing with the varying properties of dust and thus its range of interactions with light within galaxies continues to be a key issue. As galaxies evolve their chemical compositions, radiation fields, gas density distributions, magnetic fields structures and cosmic ray properties all change. These factors in turn are expected to have some influence over the composition, sizes and optical properties of dust grains. One basic question concerns the degree to which the dusty ISM of galaxies experience convergent evolution. Does the dust in giant elliptical galaxies have properties that are close to that in highly evolved spirals such as the Milky Way?

From the perspective of this meeting, we see that the effects of the ISM are no longer the wild card of unknowns that they once were thought to present. Bulk properties of nearby galaxies are seen to behave in reasonably regular ways that indicate dust properties are only mildly variable. The situation becomes a bit less clear as one goes to extreme objects. In these cases the combination of access to the absorbed and especially re-emitted light from galaxies offered by the *Spitzer* and *Herschel* space observatories, as well as ground-based millimeter and submillimeter telescopes along with improved simulations, offer a pathway to further improvements.

2. The Milky Way

Many stores in cities in the Anglophonic world display a "shop locally" sign, indicating their view of the advantages of keeping resources and often obtaining goods and services from one's own region. A similar claim can be made from the discussion of the Milky Way system in this meeting. Our home Galaxy and its companions offer tremendous advantages for studies of the SEDs of other galaxies:

- *Location:* The Sun is in the disk of the Milky Way which offers us a uniquely deep and high resolution view of a presumably fairly typical Galactic disk, as well as high quality access to its other stellar structures: bulge, halo, and nucleus.
- *Satellites:* We are even more fortunate that the Milky Way offers such a range of satellite galaxies. In particular, systems like the Magellanic Clouds are only rarely found in close proximity to giant spirals, and these allow us to study the individual stars and details of ISM structures in low metallicity, low mass star-forming galaxies.
- *6-D:* The Milky Way is the *only* galaxy where the three-dimensional spatial array of individual stars along with their space motions can be measured with any precision. Less accurate but still reasonable distances also can be obtained for interstellar clouds, thereby allowing us to build models of the true distribution of stars and gas in physical and velocity spaces.

2.1. *Stellar Populations*

When dealing with stellar populations we normally invoke what might be thought of as a kind of soft generalized cosmological principle: stellar populations throughout the universe are similar to those found in the Milky Way and its satellites. This applies particularly to low mass stars, which can only be detected in and around the Galaxy, as well as other key features of the stellar population such as binary and multiple stars along with individual intrinsic properties, such as ages, chemical abundances, and rotation. Nearby stars then offer the best tests for our models of stellar structure and evolution that form the foundations of stellar population studies in external galaxies. Our home system also is the place where the idealized concept of the existence of a stellar initial mass function (IMF) can best be directly tested by counting stellar numbers as functions of mass in a range of systems.

As we have heard, the universal IMF assumption can then be tested through studies of other, more distant systems, but without the local standard the IMF situation would be even more difficult than it already is. The good and perhaps somewhat surprising result is that thus far variations in the IMF in the key $\sim$0.5-1M$_\odot$ range, where much of the stellar mass resides, appear to be relatively small over a wide range of chemical abundance and age. Whether this pleasant congruence in the lower IMF extends to galaxies with very different evolutionary histories, such as giant ellipticals, remains uncertain.

It is less clear how routinely the low mass and upper IMFs connect in the manner seen near the Sun, and whether the slope and cutoff of the upper IMF depend on the scale of each star forming event. Uncertainties associated with the concept of a nearly universal IMF thus remain, and require quantitative measurements along with investments in theory to understand if and when significant IMF variations occur. For now, however, the standard assumption that the IMF determined in the Galaxy is a valid approximation appears to hold at a minimum in systems that are similar to our own, and does not seem to show signs of possible problems until galaxies with extremes (high or low) in star forming properties are encountered.

2.2. *The ISM*

Our location within the Milky Way's disk offers a close-up view of the structure of the ISM which reveals its high level of complexity. The densest regions, of course, are molecular and sites of star formation while the diffuse ISM actually contains a spectrum of gas densities and temperatures. This mix is pervaded by magnetic fields and cosmic rays giving rise to the synchrotron component of the Milky Way's SED. The current generation of ISM models feature the role of turbulence in transporting energy between scales and in helping to create density variations that then evolve under the effects of cooling or heating, gravity, magnetic pressures, etc. As we have seen at this meeting, the Milky Way's key position as the natural laboratory for research into the micro-physics of the ISM remains secure.

This is also an area where we are aided by an observational information explosion. The ISM of the Milky Way has been observed from the γ-rays to radio. In each spectral region we are gaining the resolution to map structures that lead to models of interactions between sources and their surroundings that also modify the emergent SEDs. An issue in this case is how best to combine the growing understanding of small scale processes into models for the interpretation of integrated properties of external galaxies?

One example of a step in this direction is offered by studies of spiral structure within the Milky Way, where we see the details of cloud formation and evolution into star forming sites, with measurements of external galaxies that offer overviews of spirals arm structures and kinematics. This investment thus leads to an improved ability to model the SED from the spiral arm components of galaxies, which in grand-design spirals are major sites for the formation of massive stars. We then saw how this approach can be expanded to a more general exploration of the role of filamentary gas structures in star formation and thus also in predicting the SED from young regions in a variety of extragalactic systems.

An even more local example of foundations supplied by the Milky Way comes from cosmic ray studies. As we have learned that cosmic ray energy densities are likely to be significant in a range of galaxies, the only direct measurements of the cosmic ray energy spectrum comes from observations made in and around the solar system. These data also provide empirical limits on the critical ratio of electron to proton cosmic ray numbers as well as indications of the chemical composition of the cosmic ray nuclei.

2.3. *The Nucleus*

Like other galaxies, the Milky Way contains a dense stellar nucleus within which lurks our supermassive black hole (SMBH). Depending on one's perspective, the low level of activity from our SMBH can be seen as unfortunate. But in any case, given the distance of ∼8 kpc to the Galactic center, we can observe our nucleus with superb precision and resolution across the electromagnetic spectrum. Many key phenomena are found to take place on small spatial scales that are impossible to directly observe in external galaxies.

How does this information then connect to the more general problem of SEDs from extragalactic systems? The most direct approach could be to consider how the various components contribute to the radiated nuclear power of the Milky Way, which then offers a template for interpreting the SEDs of other normal galaxies. The knowledge of the masses of potentially star-forming molecular clouds, their locations, and physical states gives us some idea of the range of possible states for our nucleus without and even with a significant power contribution from our SMBH.

Dealing with the nucleus is perhaps where the disparity between Galactic and extragalactic spatial scales is most prominently seen. While scales of ∼500-1000 au can be accessed in several spectral regions in the Milky Way's nucleus, our limit at M31 naturally is 100 times worse, implying a loss of a factor of $\geqslant 10^4$ in the information contained in a spatial map due to both resolution and dynamic range limits in dealing with a more distant object. And the situation is even worse for the nearest AGN, e.g. in NGC 5128 at 3.7 Mpc. Bridging this gap, and the associated chasm between power production in quiescent and highly active nuclei, is essential for improving our ability to assess the impact of nuclear activity and associated starbursts on the evolution of galaxies from measurements of their multi-wavelength SEDs.

This meeting provides a concrete demonstration of how progress in understanding the SEDs is derived from a combination of improved modelling techniques, better understanding and representations of the small scale physics, and a vast array of multiwavelength observations. We have been presented with a grand opportunity to combine multi-wavelength measurements of galaxies with varying degrees of spatial resolution, with results from simulations to derive intrinsic properties of their stars and AGN. This process is also one that does not simply fit in to one of the classic subfields of astronomy. Instead it requires a melding of multiple fields, e.g., from stellar physics to properties of interstellar dust and from stellar population to radiative transfer models as well as observations across the electromagnetic spectrum. This meeting stands as an example of the benefits that can be derived from discussions amongst experts across many fields who have related interests in common.

While the proceedings of this IAU Symposium demonstrate the excellent progress that has been achieved in the past several years, it also underscores the degree to which we are dealing with work in progress. We then can take away a few overarching points from this meeting regarding the future of inquires into the origins and evolution of the spectra of galaxies and their subsystems:

• We are passing an initial era of qualitative comparisons and moving into a time when quantitative efforts are increasingly central to further progress. On the theoretical side advances are coming from the combination of more sophisticated stellar models–interiors and atmospheres–along with improved simulations of radiative transfer through disk galaxies and around AGN. Observationally the range of multi-wavelength data on consistent flux scales, higher spectral and spatial resolution, and better laboratory data combine to support empirical improvements. To this end it might be useful to consider building a library of standardized SEDs for the best observed galaxies as a challenge for modelers.

• We have seen that conditions in the Milky Way are frequently the foundations on which models are build for interpreting other systems. It is immediately clear that this approach cannot be universal, e.g. it does not offer much insight into the SEDs of blazers. A better understanding of the circumstances under which our existing models begin to falter–e.g. how much AGN contribution, or how much of a starburst, or how low of a metallicity–could be useful in helping to focus future efforts.

• As always in astronomy, we need to be alert to identify and deal with the unexpected. In an era of surveys there can be a tendency to put aside outliers and to focus on means trends in samples. Yet a full model should be able to deal with both aspects of any sample. We need to bear in mind that some of the astrophysical "signal" from key physical processes can show up in the form of the cosmic "noise" contributed by objects with unique or unexpected properties.

3. The Infrared Universe

Our understanding of the infrared-millimeter Universe has changed dramatically in recent years thanks to ISO, Spitzer, AKARI, BLAST, many ground-based submillimeter/ millime-ter observatories, and most recently Herschel and PLANCK and the future is bright and exciting as the WISE data are released and ALMA comes on line. We heard of several interesting developments from Herschel observations, and we were treated to one of the first results from ALMA data.

Herschel has opened up the 200-500μm range to major investigation, and a result that is emerging from several studies is the widespread existence of excesses at long wavelengths, compared to greybodies with dust emissivity β=2 commonly fit to far-infrared SEDs, that may be attributed to large masses of cold dust in large disk systems. L. Dunne presented a summary of dust temperatures from redshifts up to 4 from H-ATLAS, BLAST and SCUBA, which illustrated nicely the selection bias towards warm dust emission of earlier $\lambda < 200\mu$ missions, notably IRAS, and the colder temperatures we can now access with the later missions. The newer SED templates of the H-ATLAS sample, presented in D. Smith's poster, are considerably colder than current libraries. L. Dunne finds strong evolution of the dust mass function out to z = 0.5. M. Rowan-Robinson has pointed out the importance of massive cool dust disks for some time for SCUBA and Spitzer-selected samples, and presented fits to Herschel HerMES moderate redshift galaxies which require cold dust (10-13K) that must be extended on scales of tens of kpc if optically thin.

A significant cold dust component is evident in well studied nearby galaxies. In a Herschel imaging study of M31 B. Groves demonstrated strong dust temperature gradients across the disk, with temperatures dropping below 15K at a radius of 15kpc. E. Mentuch finds the dust-to-star mass profile ratio increases with radius in M51 and that dust temperature correlates with Hα intensity, with highest temperatures in the spiral arms. G. Bendo presented Spitzer and Herschel colour maps of M81, M83 and NGC 2403 and

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by comparing with Hα and 1.6μm concludes that the 250-500μm emission originates primarily in a diffuse medium heated by evolved stars. A poster by M. Lam comes to a similar conclusion based on a worsening correlation between progressively longer wavelength Herschel-ATLAS bands and Hα for a sample of SDSS galaxies. C. Popescu described her most recent modelling of such a diffuse cool/cold disk. A similar long wavelength excess is also seen in the Sombrero, described by I. DeLooze, however she finds that cold clumps with no embedded sources provide more of the excess emission than a diffuse medium. In a poster B. Holwerda presented first results of a Herschel study of nearby edge-on disks which has the potential to determine the vertical extent of dust disks, finding that NGC 891 has a dust disk of similar size as the stellar disk plus an extended diffuse dusty component associated with the HI disk. Some ellipticals also show cold dust, as illustrated in an H-ATLAS sample with mean dust temperature 20.4K and dust mass 3.7 x 10^8 $M_\odot$ in a poster by N. Agius.

Low metallicity dwarfs have also been found to have submillimeter excesses indicating the possible existence of a cold dust component, as described by U. Lisenfeld and S. Madden. A poster by A. Remy illustrated the Herschel colours of the Herschel Dwarf Galaxies Survey, showing excess at 350μm for some systems; in some cases an excess is seen only beyond 500μm. In low metallicity systems there is the issue of how large amounts of cool dust can be effectively shielded from the strong UV radiation fields. In a study of the LMC presented in a poster, F. Galliano concludes that the 500μm excess is not likely to originate with very cold dust and may indicate grains with larger submillimeter opacity than Galactic grains. All these studies serve to emphasize that far-infrared and submillimeter emission is often not a very good tracer of the star formation rate.

An intriguing discovery of an HI disk 130 kpc in diameter in the zone-of-avoidance was presented by R. Kraan-Kortweg. This system, unlike other known giant HI galaxies, is actively forming stars at a LIRG-like rate of 35 $M_\odot$/yr. Since it's optically undetectable behind $A_v \sim 7.5$mag, it was imaged with Spitzer revealing a 50kpc star forming disk rich in PAHs. It appears to be a disk starburst building around an old bulge, perhaps a local analog of $z \sim 1$ systems with large SFRs due to large gas reservoirs in large disks.

4. Turbulence and Shocks

The longstanding question of how star formation is triggered and controlled was addressed with new data that probes turbulent processes and shocks. B. Elmegreen gave an overview of a wide range of star formation triggers – gravitational collapse in spiral-compressed gas; large rings with triggered or lingering star formation along the edges; filament collapse – based on some of the fantastically detailed images, including the Antennae, M51 and Galactic regions, available from HST and other instruments. He concludes that the overall star formation rate is governed by the total mass of cold gas and the details are dominated by complex shock dynamics. F. Boulanger presented one of the first ALMA results, which illustrates shock effects on a small scale: a compact clump in the ALMA CO(3-2) Science Verification map of the Antennae which coincides with a compact H_2 source that is a massive turbulent cloud at the interface of two complexes separated by 150 km/s. Boulanger proposed that turbulence is regulating the efficiency of star formation, quenching it when turbulence governs the gas dynamics, and that star formation proceeds when turbulent energy dissipates, based on H_2 tracing of shocked and turbulent ISM in radio galaxies, cooling flows, and other systems including Stefan's Quintet (SQ). A detailed study of SQ, which displays a massive inter-galactic shock in

H_2 containing 4 x 10^9 $M_\odot$ of cold gas with suppressed star formation, was presented by G. Natale, and the poster describing AKARI observations of SQ by T. Suzuki presented the first detection of shock-excited C[II] 158μm line emission.

5. Is There a Universal Star Formation Law?

Several talks in this meeting addressed the problem of the determination of the Star Formation Law. We should ask ourselves if there is any evidence for a universal Star Formation Law, i.e. a single slope, a single proportionality constant between SFR and mass density. Evidence does not seem very convincing, or this law depends strongly on environment. A few numbers taken from Y. Gao's talk illustrate the situation: According to Schmidt (1959), SFR $\propto \rho(HI)^n$, with $n = 1-3$, mostly $2-3$ in the ISM of our Galaxy. Kennicutt (1989) concludes that for disks the average SFR $\propto \rho(HI + H_2)^n$, but n is not well constrained, $1-3$, with a wide spread. Kennicutt (1998) compares the star formation law for total $(HI + H_2)$ gas with that derived in dense gas regions. The results are not conclusive, in dense gas regions SFR $\propto M(H_2)$ with a non-unique slope: $n = 1, 1.4, 1.7$. This key issue should be solved in the near future. One possible conclusion is that there is not a universal star formation law.

6. SPS Models and Spectral Fits

In this meeting we have seen new developments and many applications of stellar population synthesis models. Including stochastic effects in the number of stars drawn from an otherwise continuous and analytical IMF, as well as following the evolution of multiple systems (binary stars), and using evolutionary tracks computed for rotating stars, C. Leitherer has obtained a significant decrease in the M/L ratio of the model galaxies, arguing that this requires a revision of the IMF and star formation rates derived from models which ignore these effects. D. Schaerer has shown us convincingly that the effects of nebular emission should be included in the spectral models of distant star-forming galaxies if we want to determine reliable physical parameters for these galaxies. P. Prugniel has presented an interesting approach to include variable amounts of the [α/Fe] ratio in observed stellar spectra using theoretical model atmospheres to compute the differential effect in selected spectral features. He has been successful in fitting full spectra to galaxies and star clusters and measuring [α/Fe] in these systems. Several excellent talks and posters considered deriving the physical properties of galaxies by fitting optical SEDs, making some assumptions about absorption and extinction of stellar light by dust grains, and computing the energy radiated in the IR. E. Da Cunha showed how these models have been used to derive star formation histories, stellar mass, and dust content of large sample of galaxies. V. Acquaviva reminded us how the MCMC technique can be used in SED fitting to derive the best estimates for various physical parameters together with their error.

Our understanding of the relevance of TP-AGB stars in the NIR spectrum of stellar populations is not yet final. S. Meidt and S. Zibetti, as well as some already published papers, report that they do not see evidence for an increased contribution of TP-AGB stars in the NIR (w.r.t. BC03). We expect that this long lasting problem will be solved hopefully soon. Tracks should predict the right number of stars in the TP-AGB phase, and the NIR stellar SEDs used to describe these stars, including the reddening by the dusty envelope, should be as close as possible to real spectra. Physical properties like the mass of galaxies, derived from NIR-observed fluxes, depend critically on an adequate treatment of this stellar phase in population synthesis models.

It is important to understand what the results of these fits are telling us. Are these models just purely mathematical exercises, or do they resemble the physics that takes place in real galaxies? Most of the parameters that go into this modelling are quite uncertain themselves: IMF, M_{UP}, M_{LOW}, stellar metallicity distribution, number of ionizing photons, the reddening law, the amount of dust, the kind of dust, etc. What happens if we vary these quantities? How robust are the derived physical properties of the galaxies to these changes? Can we constrain these quantities from the ratio of IR to UV-optical flux or are we getting out what we put in? Tools are available to do a more detailed study that treats properly radiative transfer of radiation in a 2D or 3D stellar/dust distribution (e.g. Popescu *et al.*).

Progress in modelling stellar populations has been slow but continuous. Key issues remaining in stellar population synthesis models are being solved, as new ingredients (empirical and theoretical) become available. The advice is to use with caution the results from SPS models and fitting algorithms, and to add error bars to the values of the physical parameters that you derive.

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