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"SPACE OBSERVATIONS OF STARBURST GALAXIES"

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TECHNICAL REPORT

1. Ultraviolet Properties of Massive Stars in Starburst Galaxies

Led by JHU postdoc Gerhardt Meurer, we completed our analysis of far-UV HST FOC images of nine nearby starbursts. We have been able to delineate the structure of the regions in which the unusually vigorous star-formation is occuring (Meurer et al 1995). At 0.1 arcsec (2 to 20 pc) resolution, the starbursts are resolved into multiple clumps and bright star clusters distributed over a region several hundred pc to a few kpc in size. This suggests that compact sites of star-formation may propogate from place to place within a larger central gas reservoir over the duration of the burst. The UV and optical properties of these clusters suggest that they may correspond to newly "minted" globular clusters. These clusters typically produce about 10% to 50% of the far-UV light, and are preferentially located in the heart of the starburst, where the background UV surface brightness is highest. Thus, massive star cluster (globular cluster?) formation is a fundamental part of the starburst phenomenon. This confirms and generalizes the results of Whitmore et al (1993). Our starburst images are also being compared to our recent analysis of the HST FOC image of R136 in the LMC (De Marchi et al 1993). We have also extended our results on the UV photometric structure of starbursts to star-forming galaxies in the early universe (Meurer et al 1997). We show that the most actively- star-forming galaxies at all redshifts seem to have approximately the same bolometric surface-brightness, and that the high-redshift galaxies may be larger and more luminous versions of local starbursts.

With Carmelle Robert, we have also measured the equivalent widths and central wavelengths of ten strong far-ultraviolet absorption-lines in IUE archival spectra of a sample of 50 starburst galaxies. We have also measured the far-UV continuum fluxes and colors for each galaxy. A comprehensive literature search was also undertaken to determine the absolute visual magnitude, mass, infrared luminosity, and average metal abundance for each galaxy. All these data have been entered into a master data-base. We have conducted a detailed statistical analysis of the sample in an attempt to relate the massive star content of a galaxy to the other primary galaxian parameters. We (Heckman et al in preparation) are able to show that the low-ionization absorption- lines are primarily interstellar, while the high-ionization-lines are stellar wind lines contaminated by interstellar lines. The strengths of all these lines correlate strongly with the metallicity, luminosity, and reddening of the starburst. We believe that metallicity is the prime physical parameter controlling the strength of the stellar lines, but the strength of the interstellar lines is also determined by the dynamical state of the ISM (see section 2 below).

We are involved in several different projects (with different collabotors) to compare HST and HUT UV spectra of starbursts to sophisticated synthetic spectra that we have constructed. The synthetic spectra are discussed in detail by Leitherer, Robert, & Heckman (1995) and by Gonzalez-Delgado et al (1997). They were constructed using state-of-the-art stellar evolution models for massive stars to make synthetic H-R Diagrams (given an assumed IMF and star-formation history). The H-R Diagrams were converted into synthetic spectra using archival UV spectra of O and B stars. This allows us to predict the far-UV spectral properties of starbursts as a function of time, of assumed star-formation history, initial mass function, etc. Papers have been published in the ApJ (Robert, Leitherer, & Heckman 1993) and AJ (Gonzalez-Delgado et al 1997) describing our first set of results applying the models to IUE, HST, and HUT starburst spectra. Our HST spectra have adequate signal-to-noise and spectral resolution for us to fully realize the diagnostic potential of our model galaxy spectra. We find that the starbursts studied to date do not have similar ages, and may well have different upper-mass cut-offs in their IMF.

We are also building up a library of HST UV spectra of O and B stars in the Magellanic Clouds, as the outcome of a recently completed HST snapshot program and an approved STIS Cycle 7 project. These spectra are of interest in their own right in documenting the UV properties of metal-poor, hot, massive stars. We will use the spectra to create the first set of empirically- based synthetic UV spectra of metal-poor starbursts. This is important, because the UV-brightest starbursts (which therefore have the highest quality UV spectra) tend to be metal-poor (10% to 50% solar). This is presumably because of their low dust-content and resulting low extinction. This seems to be true both in the local universe and at high-redshift.

We (Leitherer et al 1995) also completed a program with HUT/ASTRO-2 to measure the flux from low redshift starburst galaxies shortward of the Lyman edge. The extinction-corrected Balmer emission-line fluxes combined with our HUT data for four starbursts imply that no more than a few% of the Lyman continuum is escaping from the starburst. These data provide an important constraint on models for the ionization of gas in galactic halos and in the inter-galactic medium, and suggest that QSOs - rather than protogalactic starbursts - are responsible for the ionization of the inter-galactic medium.

With collaborators Calzetti, Kinney, Koratkar, Krolik, Meurer, Robert, and Wilson, we have used archival IUE data to show that no more than about 20% of the ultraviolet continuum in Seyfert 2 galaxies (as measured in 10x20 arcsec IUE aperture) can be scattered light from a hidden type 1 Seyfert nucleus. After considering several possible alternative explanations, we concluded that the most likely origin for this light was a dusty circumnuclear starburst which produces most of the far-IR emission from these Seyfert galaxies. If true, this would make such starbursts an energetically significant part of the Seyfert phenomenon. Ultraviolet HST imaging and spectroscopic observations, together with supporting ground-based optical and near-IR spectroscopic observations, have been completed to test these ideas. The new data imply that at least half of the brightest type 2 Seyfert nuclei are indeed the sites of circumnuclear starbursts (Heckman et al 1996; Gonzalez-Delgado et al, in preparation).

In conjunction with all these efforts, we have published the results of an extensive grid of evolutionary synthesis models for populations of massive stars. The models span a range from 10% to twice solar metallicity (Leitherer & Heckman 1994). We have computed the time-dependence of the far-UV properties (HI, HeI, and HeII ionizing fluxes, strength of the Lyman edge, far-UV colors), as well as the more traditional optical and near-IR colors. These models also predict the rates at which kinetic energy and mass are returned to the interstellar medium by massive stars (vital to our work on hot gas and galactic winds - see below). Related work has been summarized by Leitherer (1993a,b) and Heckman (1994). We have also published a grid of UV spectral diagnostics for starbursts, including the line profiles of the NV, SiIV, CIV, HeII, and NIV stellar wind features (Leitherer, Robert, and Heckman 1995).

2. Hot Gas in Starburst Galaxies & Galactic Superwinds

The phenomenology and physics of the starburst-driven galactic "superwinds" has been reviewed by Heckman et al (1993a,b), Heckman (1994), Heckman (1996), and Leitherer (1994). Our goal in the projects described below is to combine the best available X-ray, UV, and optical data with numerical and theoretical models to probe the physics of these outflows and to better understand their relevance to the evolution of galaxies and the inter-galactic medium. Former JHU postdocs Michael Dahlem (now an ESA staff member at STScI) and Kim Weaver (now an Associate Research Scientist at JHU) have played key roles in this program.

We (Heckman, Dahlem, and Weaver) have defined a sample of the brightest 60 starburst galaxies observed in the IRAS survey. To date, about 40 of these have already been observed by ROSAT or are scheduled to be observed. About half of these have also been observed with ASCA. We have begun a program to analyse the ROSAT and ASCA data on each member of this sample after it enters the archives. Our long-term goal is to publish a catalog with a systematic analysis of the X-ray observations of this unique set of galaxies.

We have now completed our analysis of ROSAT PSPC and HRI data for 15 starbursts spanning a range of 1000 in luminosity: NGC55, NGC253, NGC1569, NGC1792, NGC1808, NGC2146, NGC3079, NGC3628, NGC3690, NGC4449, NGC4631, NGC4666, M82, Arp220, and Mrk 266 (Heckman 1994; Dahlem et al 1994; Junkes et al 1994; Heckman et al 1995a,b; Armus et al 1995,1997; Dahlem et al 1995a,b; Dahlem, Weaver, & Heckman 1997; Della Ceca et al 1996,1997). We find that in all these cases the X-ray emission can be traced out over volumes of truly galactic scale (diameters of 10 to 60 kpc for big galaxies and several kpc for the dwarf galaxy NGC1569).

In most of the starbursts studied so far, the galactic stellar disk is oriented nearly edge-on. In these galaxies the X-ray emission extends preferentially normal to the stellar disk (along the optical minor axis). The HRI images allow us to trace this "minor-axis" emission back into the kpc-scale central starburst, strongly suggesting that the X-ray emission is a manifestation of a galactic wind driven by the supernovae occurring in the central starburst. The close morphological relationship between the HRI images and kpc-scale loops and filaments visible in optical HÄ images suggests that we are witnessing the interaction between the wind and dense ambient material. The kinematics and physical state of the emission-line gas also supports this interpretation.

PSPC and ASCA spectra of these starburst galaxies clearly show the presence of at least two different emission components: a hard component (either a flat powerlaw, or thermal emission with kT >> keV) and a softer component (kT = several hundred eV to 1 keV). The soft component dominates in the galaxy halo, while the hard component dominates in or near the starburst. Thus, the soft thermal component comes from shock-heated material powered by the galactic wind. The hard component is most likely due to X-ray binaries, but inverse Compton X-rays produced by the interaction of the IR photons from the starburst with relativistic electrons, very hot supernova-heated gas, or an optically-obscured AGN may also contribute. The temperature of the halo gas appears to be independent of the depth of the galaxy potential, and it appears that the hot gas can escape the less massive galaxies will (possibly) being retained by the most massive galaxies. This may tell us how the IGM was enriched with metals and explain why their is a strong mass-metallicity relation for galaxies.

We have also begun an X-ray and optical investigation of the physical and dynamical state of the diffuse interstellar medium in the disks of the nearest and largest (angular size) normal star- forming galaxies. We are using archival ROSAT and ASCA data to determine the structure, temperature, and energy content of the hot (> million K) gas and using deep optical images (H-Alpha, U, and R) and long-slit spectra to isolate energy sources (OB stars and their byproducts) and determine how the diffuse warm gas (T = 10000 K) is energized. We hope that such a multiwavelength comparison of the ISM in normal galaxies and starburst systems will provide a unique test of comprehensive models of how massive stars affect the ISM (Wang et al 1997).

We have also completed the contruction of a series of numerical hydrodynamical models of X-ray nebulae produced by starburst-driven outflows (Suchkov et al 1994; 1996). The aim is to use these models to elucidate the physical processes responsible for the galactic-scale X-ray nebulae we observe with ROSAT and ASCA. A simplified analytic treatment of outflows from dwarf starburst galaxies was also developed by DeYoung & Heckman (1994).

The new HST and HUT ultraviolet spectra (plus the archival IUE spectra) contain a wealth of data on the cooler phases of the interstellar medium in starbursts. We see strong UV absorption- lines from species ranging in ionization potential from CI to OVI. These interstellar lines are typically very broad (FWHM = few hundred to 1000 km/s) and the line centroids appear to be blueshifted (by typicall several hundred km/s) with respect to systemic velocity. We seem to be seeing highly turbulent gas flowing out of the central starburst. Since these lines lie on the saturated part of the curve-of-growth, their strength is primarily controlled by the velocity dispersion in the absorbing gas. Since the gas motions probably have both a gravitational and hydrodynamic component, this may explain the correlation of the line strength with both galaxy mass and starburst luminosity (Heckman et al in preparation).

3. The Effect of Dust on the UV, Optical, and Infrared Properties of Galaxies

In collaboration with JHU/STScI postdoc Boqi Wang, we (Wang & Heckman 1995) completed an analysis of the far-UV, optical, and infrared properties of galaxies using the IRAS database and space- UV (200 nm) observations. We have found that the dust-opacity of normal and starburst galaxies (and hence their transparency in the optical and ultraviolet) depends on the fundamental galaxian properties of mass, luminosity and metallicity. The optical depth of the dust in star-forming galaxies is larger in galaxies that are more luminous and/or more massive. These dependences have been modeled by a simple thin slab model. We suggest that more luminous galaxies are more opaque because they have more dust per unit gas mass (higher metallicity) and are geometrically thicker as well. The simple models suggest that only the most luminous star-forming galaxies may be optically thick in the visible.

We (Meurer et al 1995;1997) have also used the UV colors (measured with IUE) and the ratio of far-IR to UV flux to show that much of the dust responsible for reddening the starburst and for re-radiating this starlight in the far-IR, is located in a shell- like structure surrounding the starburst (i.e., a foreground screen), rather than being well-mixed with the stars. This is an unexpected result, and suggests that dust grains may be destroyed in the starburst and/or transported out of the starburst. Recent near-IR and optical spectroscopy of the HI recombination-lines in starbursts by D. Calzetti also supports the foreground-screen model for the extinction.

We (Calzetti et al 1995) have also studied the role of the heating of dust in starbursts by both the ionizing (Lyman continuum) and non-ionizing radiation. We conclude that both sources are needed to explain the far-IR properties of starburst and star-forming galaxies. We find that the amount of absorbed optical and UV radiation (as deduced using IUE plus optical spectra) can account for essentially 100% of the emission from the cool dust and about 70% of the emission from the warm dust. Destruction of Lyman continuum photons by dust may complicate the use of HI recombination lines to determine the hot-star population in starbursts. In agreement with other studies (e.g. Bothun, Lonsdale, & Rice 1989), we find that a determination of the star- formation rate from the far-IR luminosity can only be done after the contribution of the cool dust heated by the diffuse stellar radiation field has been removed from the IRAS fluxes.

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