Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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The energetic role of massive stars in the AGN phenomenon

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Abstract. I review the evidence for a possible connection between AGN and starbursts and assess the energetic role of massive stars in the AGN phenomenon. My particular focus is on UV spectroscopy, since this is the energetically dominant spectral regime for the hot high-mass stars that power starbursts, and contains a wealth of spectral features for diagnosing the presence of such stars. I also review the non-stellar sources of UV line and continuum emission in AGN, including scattered or reprocessed light from the 'central engine'. Spectroscopy directly shows that hot stars provide most of the UV light in about half of the brightest type 2 Seyfert nuclei and UV-bright LINERS. The population of hot stars in these AGN is typically heavily extinct and reddened by dust with $A(1600\text{Å}) \simeq 2$–4 mag. The implied intrinsic UV luminosities of the starburst range from 10^8 to 10^9 $L_\odot$ in the LINERS to 10^{10} to 10^{11} $L_\odot$ in the type 2 Seyferts. Massive stars play an energetically significant role in many AGN, but the causal or evolution connection between starbursts and AGN is unclear. I also consider the energetics of massive stars and accreting supermassive black holes from a global, cosmic perspective. Recent inventories in the local universe of the cumulative effect of nuclear burning (metal production) and of AGN-fueling (compact dark objects in galactic nuclei) imply that accretion onto supermassive black holes *may* have produced as much radiant energy as massive stars over the history of the universe.

1. Introduction

Perhaps the most important unanswered question concerning the AGN phenomenon is the fundamental nature of the energy source. There are sound theoretical arguments in favor of accretion onto supermassive black holes (*e.g.*, Rees 1984), and the observational evidence that such 'beasts' exist is growing (Richstone *et al.* 1998). On the other hand, circumnuclear starbursts can have bolometric luminosities that rival even powerful quasars (*cf.* Sanders & Mirabel 1996 and references therein), and there have been recurring suggestions that starbursts may play an important role in the Seyfert galaxy phenomenon (*e.g.*, Perry & Dyson 1985; Terlevich & Melnick 1985; Norman & Scoville 1988; Cid Fernandez & Terlevich 1995).

Ultraviolet observations are crucial in interpreting both starbursts and AGN, and in probing a possible relationship between them. First, the vacuum-UV is the energetically-dominant spectral regime for the hot massive stars that power starbursts, and the UV is also the single most energetically-significant regime for quasars and type 1 Seyfert nuclei (*cf.* Elvis *et al.* 1994). Second, the vacuum-UV contains a wealth of spectral features including the resonance transitions of most cosmically-abundant ionic species. These give UV spectroscopy a unique capability for diagnosing the (hot) stellar population and the physical and dynamical state of gas in galactic nuclei.

During this talk I will summarize observations that probe the energetic role of massive stars and starbursts in the AGN phenomenon. I will concentrate primarily on UV observations and on relatively nearby AGN, starting with the most common and least powerful type ('LINERs') and then the best-studied type of AGN (Seyfert nuclei). I will conclude with an assessment of the global energetic significance of massive stars and AGN over the history of the universe.

2. 'Building blocks' for the UV and optical light in AGN

Since this is not an audience of 'AGN-ophiles', I will begin with a brief primer concerning the inner workings of AGN and the diverse sources of their UV and optical light.

2.1. The central engine

According to the current paradigm, AGN are primarily powered by accretion onto a supermassive black hole (the 'central engine'). One of the primary outputs of this central engine is UV and optical continuum radiation (possibly from an accretion disk). This continuum illuminates and photoionizes a swarm of dense gas clouds that move towards/out- from/around the 'central engine' with velocities of several thousand km s^{-1}. The clouds produce strong, broad UV and optical emission-lines, and this 'Broad Line Region' (BLR) is one of the defining properties of quasars and type 1 Seyfert nuclei. The continuum source and BLR are sub-pc in scale, based on their relatively rapid variability.

The central engine is surrounded by a larger ($\gg$ pc-scale) optically and geometrically-thick structure (the 'obscuring torus') that absorbs the optical, UV, and soft X-ray emission from the central engine and reprocesses it mostly into thermal IR emission from dust in the torus (*cf.* Pier & Krolik 1993). For objects viewed near the polar axis of the torus, we have a direct view of the central engine. These are variously classified as type 1 Seyfert nuclei (if of low luminosity) or quasars (if of high luminosity). The central engine is occulted for objects viewed near the equatorial plane of the torus, and these are classified as type 2 Seyfert nuclei. The polar axis of the torus also coincides with the radio jet axis, even in radio-quiet AGN with weak jets (Wilson & Tsvetanov 1994).

2.2. Reflected light from the central engine

Light from the central engine can also be reflected off of electrons or dust grains located out along the polar axis of the torus, thereby allowing the central engine to be viewed indirectly in type 2 Seyfert nuclei. This reflected component can be isolated most cleanly in polarized light (*cf.* Tran 1995 and references therein). An electron 'mirror' will be kept warm and ionized by the incident radiation from the central engine (*cf.* Krolik & Kriss 1995).

Such reflection should preserve the equivalent widths of the BLR emission-lines with respect to the UV continuum from the central engine. However, if the mirror is made of warm electrons, the BLR emission-lines can be broadened significantly upon reflection (*cf.* Cid Fernandez & Terlevich 1995).

2.3. Reprocessed light from the central engine

Hard radiation from the central engine that escapes along the polar axis of the obscuring torus can photoionize and heat distant gas clouds, causing them to emit the usual UV and optical collisionally-excited and recombination lines. Gas in this illuminated region is observed to have a velocity dispersion of a few hundred $\mathrm{km\,s^{-1}}$, and this region is therefore dubbed the Narrow- Line Region ('NLR'). It has a typical scale of 10^2 to 10^3 pc and thus can be spatially-resolved with *HST* in nearby AGN.

Both the NLR clouds and the warm gas in the 'mirror' are also expected to produce UV nebular continuum emission (free-free, Balmer continuum, and 2-photon continuum). Generally, the UV continuum produced by such gas would be weak relative to the associated emission-lines, unless the gas is quite hot ($\gg 10^5$ K). In this case, free-free emission dominates the continuum (*cf.* Tran 1995; Krolik & Kriss 1995).

2.4. A starburst

Starbursts have very characteristic UV spectral properties. The UV spectral lines observed in starbursts are due to both stars and interstellar gas. The strongest and most dramatic stellar features in a starburst are due to stellar winds, leading to relatively broad ($\sim 2000\ \mathrm{km\,s^{-1}}$) and blueshifted absorption features with a weak P-Cygni emission component. Stellar photospheric lines (both resonance lines and excited transitions) are also present, and are relatively narrow and unshifted in velocity. Finally, interstellar gas produces strong resonance lines in absorption, with typical widths of several-to-many hundred $\mathrm{km\,s^{-1}}$ and (often) with comparably-large blueshifts indicative of outflows (*cf.* González-Delgado *et al.* 1998a). Of course the presence of interstellar absorption-lines alone would not provide any direct evidence for the presence of hot stars in an AGN.

The spectral energy distribution of the vacuum-UV continuum in starbursts is insensitive to the age and initial mass function of the starburst (*cf.* Leitherer & Heckman 1995). This means that the observed UV colors can be used to estimate the amount of extinction, and hence to derive a 'bolometric correction' to the UV luminosity (*e.g.*, Meurer, Heckman & Calzetti 1999).

3. Massive stars in LINERs

The term LINER is an acronym for Low Ionization Nuclear Emission- line Region (Heckman 1980), a phenomenon that is nearly ubiquitous in the nuclei of galaxies of early to mid Hubble type. The most recent and comprehensive analysis of LINERs is due to Luis Ho and his colleagues (*cf.* Ho, Filippenko & Sargent 1997) who argue that most LINERs are low-level AGN (presumably supermassive black holes radiating at a highly sub-Eddington rate). As such they may be the 'fossil remains' of the quasars that dominated the early universe. While many LINERs are likely to be mini-AGN, Terlevich & Melnick (1985), Filippenko

& Terlevich (1992), Shields (1992), and Heckman (1996) have argued that a significant fraction of LINERs could also be metal-rich starbursts. These issues are discussed in many papers in the volume edited by Eracleous *et al.* (1996).

Maoz *et al.* (1995) conducted a vacuum-UV (2300 Å) imaging survey of nearby galaxies with the *HST* and detected bright, point-like UV sources in only 5 of the 23 LINERs in the sample. They argue that the detected UV sources are bright enough (if they are AGN) to produce the observed LINER via photoionization in these 5 cases. The 'UV-dark' sources are then cases in which either *(i)* the LINER is shock-heated rather than photoionized; *(ii)* the 'central engine' in the LINER is obscured (analogous to the case of type 2 Seyfert nuclei); or *(iii)* the central UV source is temporarily 'turned off'. Barth *et al.* (1998) analysed *HST* UV images of a larger sample of LINERs and favor dust-obscuration as the cause of the low detection rate.

Spectroscopy of the UV-bright LINERs with *HST* reveals a diverse set of properties. In the cases of M 81 (Ho, Filippenko & Sargent 1996) and NGC 4579 (Barth *et al.* 1996) the UV spectra are generally consistent with the interpretation of LINERs as low-level AGN (including the presence of a BLR and evidence for significant UV variability). The LINER in the near-nuclear region of M 87 seems better explained as arising from gas heated by high-speed shocks (Dopita *et al.* 1996). UV spectroscopy of the LINERs in NGC 4594 (Nicholson *et al.* 1998) and NGC 6500 (Barth *et al.* 1997) show weak, narrow emission-lines and a faint UV continuum of uncertain origin (due to the low signal-to-noise in the data).

Maoz *et al.* (1998) have recently published an analysis of *HST* UV spectra of a sample of seven UV-bright LINERs. They find that in three cases (NGC 404, NGC 4569, and NGC 5055) the nuclear UV source is actually a highly-luminous super star cluster with a pronounced O-star population (based on the detection of broad C IV and Si IV stellar wind features). Ground-based optical and near-UV spectra of the nucleus of NGC 4569 also corroborate the 'super star cluster' interpretation (Keel 1996). Of the other four members of their sample, two (M 81 and NGC 4579) are clearly mini-AGN and two (NGC 4594 and NGC 6500) can not be reliably classified. Interestingly, the three LINERs whose UV emission is produced by hots stars are much weaker X-ray sources than the AGN-powered LINERs (*i.e.*, they have X-ray properties that are consistent with starbursts). Moreover, NGC 4569 and NGC 5055 are members of the so-called 'transition- class' LINERs that have spectral properties intermediate between 'classical' LINERs and low-excitation H II regions (Filippenko & Terlevich 1992; Ho, Filippenko & Sargent 1997). This is the LINER sub-class that Heckman (1996) and Filippenko & Terlevich (1992) have proposed may be metal-rich starbursts.

The UV spectral energy distributions of the three 'star-powered' LINERs are much redder than the intrinsic spectrum of a young starburst population. Thus, Maoz *et al.* argue that these nuclear star clusters must be heavily reddened and extincted by dust. Using the semi-empirical approach for correcting the UV spectra of starbursts for the effects of dust (*cf.* Meurer, Heckman & Calzetti 1999), the measured UV colors for these three LINERs imply extinctions of 2 to 4 magnitudes at 1600 Å. The implied intrinsic UV luminosities of the nuclear star clusters are then in the range $\sim 10^8$ to 10^9 $L_\odot$. These luminosities are at the low-end of the range of classical starburst galaxies, but in these LINERs the UV emission is produced by a single compact super star cluster with a radius no larger than a few pc! In the cases of NGC 404 and NGC 4569, the intrinsic UV luminosities are similar to the total galactic far-IR luminosity measured by *IRAS* and of-order 10^{-1} of the bolometric luminosity of the entire galaxy.

Thus, at this stage it appears that the term 'LINER' encompasses at least two separate classes of objects. One type is primarily powered by hot, massive stars (*e.g.*, a compact, dusty, metal-rich nuclear starburst). The other is a true 'low-power-AGN' presumably fueled by low-level (and/or low-effciency) accretion onto a nearly dormant supermassive black hole. The statisics are quite uncertain so far, but it seems likely that the two types of LINERs are roughly equally common.

4. Massive stars in the nuclei of Seyfert galaxies

The nuclei of Seyfert galaxies have luminosities that range from those of LINERs to those of quasars (indeed type 1 Seyfert nuclei can be fully regarded as low-power quasars). In order to assess the energetic role of massive stars in these powerful AGN via UV or optical spectroscopy, it is clearly preferable to focus on those objects in which the obscuring torus has providentially blocked out the blinding glare from the central engine (thereby allowing us to study the fainter surrounding 'circumnuclear' region without squinting). Thus, my collaborators and I have focused our attention on the nuclei of type 2 Seyfert galaxies.

Type 2 Seyfert nuclei have long been known to exhibit a 'featureless continuum' ('FC') that produces most of the UV light and typically 10% to 30% of the visible/NIR light (the rest appears to be light from an ordinary old population of stars). Until recently, it was thought that the optical/UV FC was light from the hidden type 1 Seyfert nucleus that had been reflected into our line-of-sight by warm electrons and/or dust. However, recent optical spectropolarimetry (Tran 1995) shows that this is not the case: most of the optical FC must have some other origin, since it is significantly less polarized than the reflected broad emission-lines. Similarly, we (Heckman *et al.* 1995, hereafter H95) examined the vacuum UV (1200–2000 Å) spectral properties of a large sample of type 2 Seyferts using *IUE* data and showed that the lack of any detectable reflected emission from the BLR meant that at least 80% of the UV continuum must have some other origin.

Two possibilities for the optical/UV FC have been advanced. The first (Tran 1995) is that the unpolarized (unreflected) component of the FC is produced by thermal emission from hot (10^{5-6} K) gas heated in some way by the central energy source. The second (Cid Fernandes & Terlevich 1995) ascribes the unpolarized FC to a dust-shrouded starburst possibly associated with the obscuring torus. The weakness of the observed line UV emission led H95 to rule out a primarily nebular origin for the UV continuum, and to argue instead that the 'dusty starburst' interpretation is the more plausible one (at least for the UV-bright members of the H95 sample). Moreover, we also showed that the starburst hypothesis can be correct only if the bulk of the observed far-IR continuum from these type 2 Seyferts is re-radiated starburst light. The large far-IR luminosities would then imply that starbursts are an energetically significant component of the Seyfert phenomenon.

However, the *IUE* data do not have adequate signal-to-noise to unambiguously detect stellar absorption-lines in the Seyferts. Thus, they provide only indirect and inconclusive evidence for a starburst component in the FC of type 2 Seyferts. To directly test this requires the spectroscopic detection of an unusually luminous population of young stars, and this is best accomplished in the vacuum UV using strong stellar wind lines and weaker stellar photospheric lines (*cf.* Leitherer, Robert & Heckman 1995; Heckman & Leitherer 1997). With data of suitable quality, a young stellar component may also be detected in the blue and near-UV via high-order Balmer absorption- lines, He I absorption-lines, and the Balmer edge from hot stars (*e.g.*, González-Delgado *et al.* 1997).

We therefore undertook a program to obtain high-resolution vacuum UV images and spectra (with *HST*) and near UV spectra (with ground-based telescopes) of a representative sample of the brightest type 2 Seyfert nuclei. These results have been presented in detail in Heckman *et al.* (1997) and González-Delgado *et al.* (1998b). *HST* imaging shows that the UV continuum source in every case is spatially-resolved (scale size few hundred pc or greater). In some cases the morphology is strikingly reminiscent of UV images of starbursts (compare Fig. 1 to images in Meurer *et al.* 1995). In other cases (*cf.* Capetti *et al.* 1996), a component of the UV continuum is roughly aligned with the inferred polar axis of the obscuring torus (as expected for reflected and/or reprocessed light from the central engine).

Of the sample of 13 type 2 Seyfert with *HST* vacuum-UV images, only four are bright enough for us to obtain spectra of adequate quality in the crucial UV spectral window from about 1200 to 1600 Å. However, these spectra are decisive: all four show the clear spectroscopic signature of a starburst population that dominates the UV continuum (Fig. 2). In addition to classic strong stellar wind features (N V λ1240, Si IV λ1400, and C IV λ1550), we can also detect weaker and much narrower absorption features from excited transitions (which are therefore indisputably of stellar origin — *cf.* Heckman & Leitherer 1997; Heckman *et al.* 1997; González-Delgado *et al.* 1998b).

In each of the four cases, if we use the empirical 'starburst attenuation law' (Calzetti, Kinney & Storchi-Bergmann 1994; Meurer, Heckman & Calzetti 1999) to correct the observed UV continuum for dust extinction, we find that the bolometric luminosity of the nuclear (10^2-pc-scale) starburst is comparable to the estimated bolometric luminosity of the 'hidden' type 1 Seyfert nucleus (of-order $10^{10}\,L_\odot$). The large-aperture *IUE* spectra imply the existence of a surrounding larger-scale (few kpc) and more powerful (few $\times\,10^{10}$ to $10^{11}\,L_\odot$) dusty starburst that is energetically capable of powering the bulk of the observed far-IR emission from the galaxy. Thus, starbursts are an energetically significant (or even dominant) component of at least *some* Seyfert galaxies.

However, we have *HST* spectra of only four type 2 Seyferts, and these are strongly biased in favor of cases with high UV surface- brightness. Can we say anything more general? To address this, we have embarked on a program to obtain spectra from about 3500 to 9000 Å of a complete sample of the 25 brightest type 2 Seyfert nuclei in the local universe. These objects are selected from extensive lists of known Seyfert galaxies on the basis of the flux of either

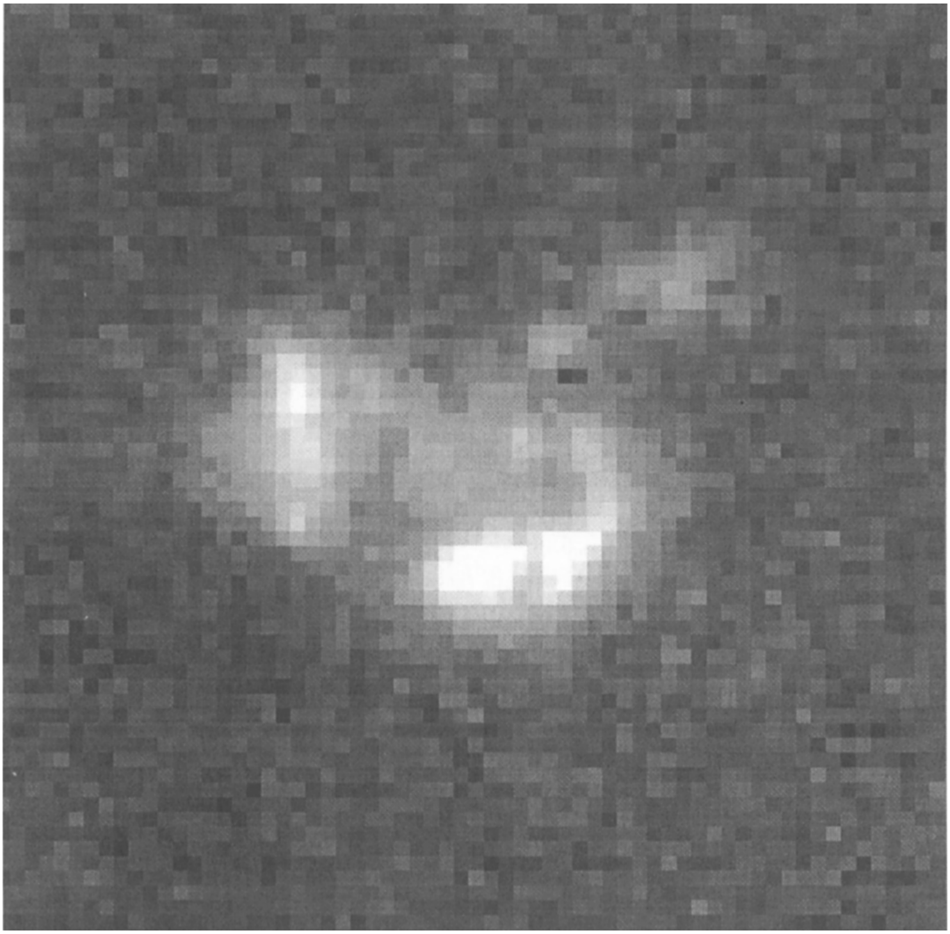

Figure 1. *HST*-FOC image of the vacuum-UV (2200 Å) continuum emission in the nucleus of the type 2 Seyfert galaxy NGC 7130. The region displayed is about 0.5 kpc across. This image is morphologically-similar to those of typical starbursts, including the presence of bright UV knots corresponding to super star clusters.

the nebular line-emission from the Narrow Line Region (the [OIII]λ5007 line) or of the nuclear radio source (Whittle 1992).

We are still analysing these spectra, but even a cursory inspection of the near UV region (below 4000 Å) shows that about half have pronounced Balmer absorption-lines whose strength is consistent with a population of late O-type or early B-type stars. In several cases we can also detect those photospheric He I absorption-lines (λ4921, λ4387, λ3819) that are not filled in by nebular emission. This group of nuclei includes three of the four objects with *HST* vacuum UV spectra. In most of the remainder of the sample, the 'FC' is so weak relative to the light from a normal old-bulge stellar population that its origin is still not clear. There are also several cases in which the Balmer emission-lines from the

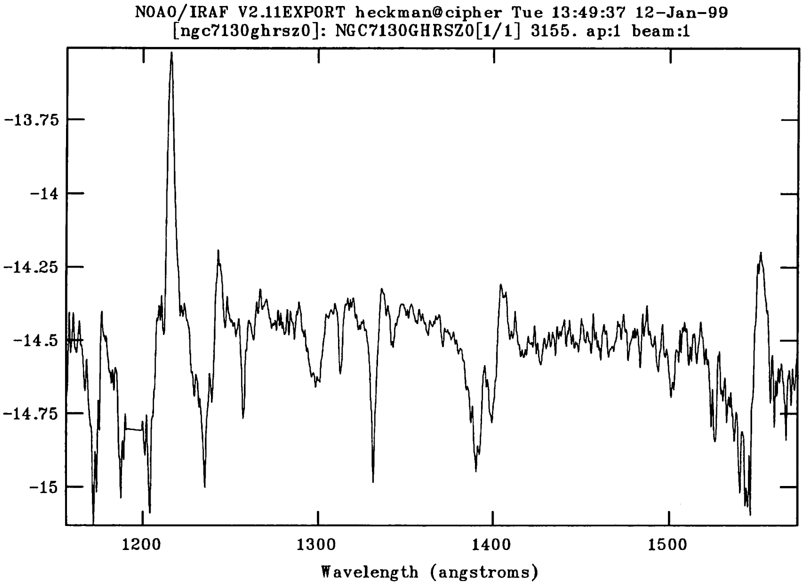

Figure 2. *HST*-GHRS vacuum-UV spectrum of the the nucleus of the type 2 Seyfert galaxy NGC 7130 ($\log F_\lambda$ *vs.* λ). This spectrum was obtained of the region shown in Fig. 1. Note the broad, blueshifted stellar wind lines due to C IV λ1550, Si IV λ1400, and N V λ1240 and the unshifted stellar photospheric line due to the excited Si III λ1299 and S V λ1502 multiplets. The other strong narrow lines are interstellar in origin. Comparing this spectrum to starburst spectra, the only noticeable differences are the strong nebular Lyα, NV, and C IV emission-lines in NGC 7130, which are excited by the ionizing radiation from the hidden 'central engine'.

NLR are so strong in the near- UV that they overwhelm any putative stellar absorption features. Fortunately, the *HST* vacuum-UV spectrum of one of these (Mrk 477) leaves no doubt that it contains a starburst (Heckman *et al.* 1997). Recent work in a related vein has been undertaken by Cid Fernandes, Storchi-Bergmann & Schmitt (1998) and Schmitt, Storchi-Bergmann & Cid Fernandes (1999). Their results agree at least qualitatively with ours: they find that most of the optical and near-UV 'FC' in type 2 Seyfert nuclei is produced by young and intermediate age stars (age $\leq$ 100 Myr).

Thus, it is clear that massive stars and starbursts play an important energetic role in a significant fraction of Seyfert nuclei. What is not yet clear is whether starbursts are an *essential* component of the Seyfert phenomenon and what (if any) the causal or evolutionary connection might be. Perhaps — as Cid Fernandes & Terlevich (1995) suggested — the starburst is an inevitable byproduct of the dense molecular torus that is now believed to be a fundamental part of the inner machinery of Seyferts (both obscuring the central engine and serving as a reservoir of fuel).

5. Massive stars vs. Black Holes: a global perspective

In closing my talk, I'd like to step back and consider the issue of the relative energetic significance of massive stars and AGN from the most global perspective possible. That is, over the course of cosmic time, how much radiant energy has been produced by massive stars and how much has been produced by accretion of matter into supermassive black holes?

First, we can conduct an inventory of the luminous energy present in the universe today. This represents the cumulative effect of the production of luminous energy over the history of the universe diminished only by the $(1+z)$ stretching of the photons. This inventory is made possible by the recent ultra-deep near-UV-through-near-IR galaxy counts in the Hubble Deep Field (Pozzetti *et al.* 1998) on the one hand, and the landmark detection by *COBE* of a far-IR/sub-mm cosmic background on the other (Puget *et al.* 1996; Hauser *et al.* 1998; Schlegel, Finkbeiner & Davis 1998).

The total present-day energy density contained in the cosmic IR background is $\sim 6 \times 10^{-15}$ erg cm^{-3} (Fixsen *et al.* 1998), which is comparable to the total energy density contained in the NUV-through-NIR light due to faint galaxies (Pozzetti *et al.* 1998). The origin of the latter is clear: the light of these faint galaxies is overwhelmingly due to ordinary stars (nuclear fusion). However, the origin of the cosmic IR background is *not* so clear. As I will outline below, simple 'from-first-principles' arguments imply that this luminous energy may have been generated predominantly by either stars or AGN that were deeply shrouded in dust.

One obvious way to evaluate whether stellar nucleosynthesis could have been responsible for producing the energy contained in the cosmic IR background is to take an inventory of the byproducts of nuclear burning in the local universe. The recent compilation assembled by Fukugita, Hogan & Peebles (1998) implies that the baryonic content of galaxies, the intracluster medium, and the general intergalactic medium is $\Omega_B \simeq 4.3 \times 10^{-3}$, 2.6×10^{-3}, and 1.4×10^{-2} respectively. If we adopt a mean metallicity of 1.0, 0.4, and 0.0 $Z_\odot$ for these respective baryonic repositories and use the estimate due to Madau *et al.* (1996) that each gram of metals produced corresponds to the generation of 2.2×10^{19} erg of luminous energy, the implied co-moving density of energy produced by nuclear burning is then 2×10^{-14} erg cm^{-3}. If we instead assume that the ratio of metals inside galaxies to those outside galaxies is the same everywhere as it is in clusters of galaxies (*cf.* Renzini 1997), then the total mass of metals today is about twice as large as the above estimate, as is the associated luminous energy. To compare these values to the cosmic IR background, we need to know the mean energy-weighted redshift at which the photons in the IR background originated. Taking $<z> = 1.5$, the resulting observable energy density in the present universe would be in the range 8 to 16×10^{-15} erg cm^{-3}. This is comparable to the sum of the energy contained in the IR plus the NUV-through-NIR backgrounds. Thus, there is no fundamental energetics problem with a stellar origin for the cosmic IR background.

What about dusty quasars? At first sight, this does not appear to be a plausible source for the bulk of the cosmic IR background. The cumulative emission from the known population of quasars — selected by optical, radio, or X-ray techniques — has resulted in a bolometric energy density today of about

$3 \times 10^{-16}\,\mathrm{erg\,cm^{-3}}$ (*cf.* Chokshi & Turner 1992), only about 5% of the cosmic IR background. But, what if there exists a substantial population of objects at high-redshift that are powered by accretion onto supermassive black holes, but which are so thoroughly buried in dust that they radiate primarily in the IR, and have thus far been missed in quasar surveys? That is, could the cosmic IR background be produced by a population of dust-enshrouded AGN at high redshift? Might the population of the dusty sub-millimeter sources recently detected by *SCUBA* be our first glimpse of this population (*e.g.*, Smail *et al.* 1998; Lilly *et al.* 1998; Ivison *et al.* 1998)? Could this same population of dust-enshrouded AGN be responsible for the bulk of the cosmic hard X-ray background (as Fabian *et al.* 1998 have argued)?

One way to assess whether accretion onto supermassive black holes is an energetically feasible source for the observed cosmic IR background is to examine the fossil record in nearby galaxies. The generation of the cosmic IR background by the accretion of matter onto supermassive black holes necessarily implies that the centers of galaxies today will contain the direct evidence for this accretion. Is there enough mass in the form of supermassive black holes in galaxies today to have produced the IR background?

Recent dynamical surveys of the nuclei of nearby galaxies strongly suggest that supermassive black holes are common or even ubiquitous, with a mass that is $\sim 0.5\%$ of the stellar mass of the spheroid (bulge or elliptical) within which the black hole resides (Magorrian *et al.* 1998; Richstone *et al.* 1998). The corresponding ratio of black hole mass to spheroid blue luminosity in solar units is roughly 0.045 for a typical elliptical galaxy. Fukugita, Hogan, Peebles (1998) estimate that the present-day blue luminosity density associated with spheroids is $4.6 \times 10^7\,\mathrm{L_\odot Mpc^{-3}}$, so the implied mean density in the form of supermassive black holes is $\sim 2 \times 10^6\,\mathrm{M_\odot Mpc^{-3}}$.

If we assume that accretion onto a supermassive black hole releases luminous energy with an efficiency $\epsilon = 10\%\,c^2$, the present-day black hole mass density implies a total production of $1.2 \times 10^{-14}\,\mathrm{erg\,cm^{-3}}$ in co-moving coordinates. If the energy-weighted mean redshift at which this was emitted is $z \simeq 2$, the present-day luminous energy density is then $4 \times 10^{-15}\,\mathrm{erg\,cm^{-3}}$. This is roughly an order-of-magnitude larger than the luminous energy produced by the known quasar population, but matches the energy contained in the cosmic IR background rather well.

There are therefore three possible interpretations of this. First, we may have substantially over-estimated the mass of black holes in the nuclei of galaxies today. Second, the formation of a supermassive black hole may occur with a mean efficiency for the production of radiant energy that is small (*e.g.*, 1% rather than 10%). Perhaps the quasar phase corresponds to high efficiency and produces most of the radiant energy, but most of the accretion and black hole growth produces very little radiation (*e.g.*, Narayan 1997). Third, maybe the cosmic IR background does have a substantial contribution from dust-enshrouded AGN. If true, this would imply that over the history of the universe, accreting supermassive black holes have produced as much luminous energy as stars!

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Discussion

Maeder: Can you, please, comment a bit more on the various possible causal connections between the central body and the starburst?

Heckman: This is speculation, but there are a number of interesting possibilities. We know that an essential component of Seyfert nuclei is the so-called ‘obscuring torus’ which is tens of pc in size and made of dusty molecular gas. Intense star-formation in this torus seems very likely, and it may be that the somewhat larger starbursts we are seeing are simply the outer regions of the same structure. Some of the gas in the starburst may funnel into the torus, and the torus may in turn feed the central supermassive black hole. It is also possible that outflows from the central AGN could compress the dense circumnuclear ISM and trigger a starburst.

Cid Fernandes: How do you think Mrk 463E, Mrk 477 and Mrk 1210 will look like some 50–100 Myr from now? Will they still be Seyfert 2 galaxies?

Heckman: That is a question that I would love to know the answer to! Your recent spectroscopic analysis suggests that many Seyfert 2's contain what might be called a 'postburst' (10^8 year) population, so perhaps younger starbursts like the ones you named are the precursors to these objects.

Kaper: The (restframe) UV spectra of Broad Absorption Line QSO's resemble hot-star spectra very much, a big difference being, however, the 10 × larger v_∞ measured in QSO BALs. In these systems, the P-Cygni profiles are thought to be due to an outflow, not to a population of massive stars. Could you comment on this?

Heckman: I don't think nature would be perverse enough to arrange for a sub-type of the BAL phenomenon that would occur in type 2 Seyfert nuclei and exactly mimic the line profiles of O-type stars. We also see photospheric lines from O- and early B-type stars in the Seyfert nuclei, and these are not present in BAL QSO's. In the Seyfert 2 nuclei I am convinced that we are observing rather normal starburst stellar populations. The purely interstellar absorption-lines that we observe in the Seyfert nuclei do show that outflows of gas at few hundred km s^{-1} are occuring. These flows may be driven by the AGN or the starburst itself (similar outflows are commonly observed in pure starbursts).

Schulte-Ladbeck: How important, in your opinion, would be a future UV spectropolarimetry space mission to advance this field?

Heckman: Well, spectropolarimetry has played an absolutely crucial role in developing the over-arching 'unification' paradigm for AGN. Spectropolarimetry in the UV would be especially powerful, given the rich array of diagnostic lines and the high scattering effciency of dust in this spectral region.