

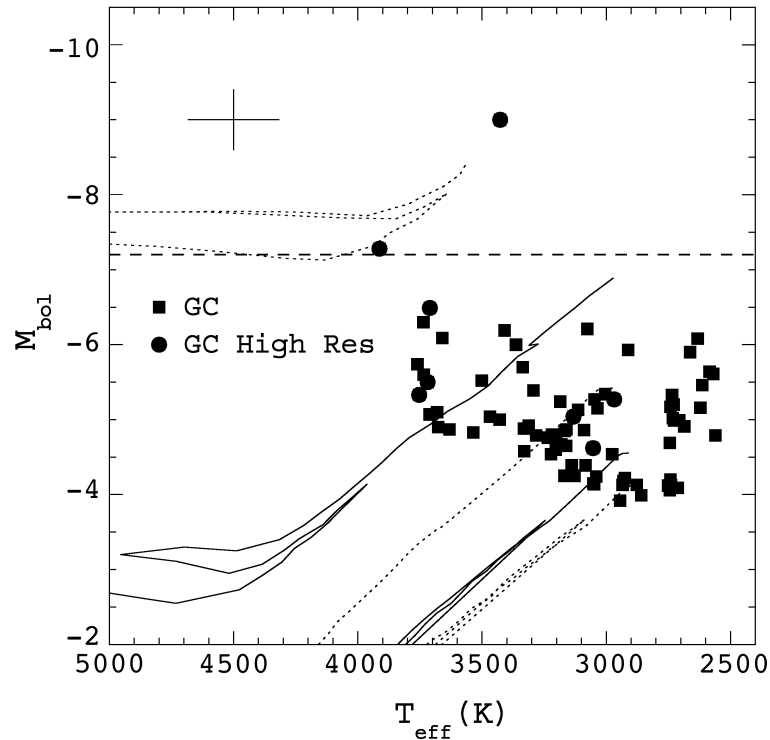


## Star Formation History at the Galactic Center

Bob Blum (NOAO)

There are some really cool stars in the Galactic Center. In fact, the Galactic Center is so chock-full of interesting objects and phenomena that it sometimes seems mysterious or at least overly complicated. However, three decades of work have shed amazing light on the nucleus of the Milky Way since it was first observed in stellar light by Eric Becklin and Gary Neugebauer in 1968 (*ApJ*, 151, 145). Not long after, Bruce Balick and Robert Brown (1974, *ApJ*, 194, 265) identified the strong and compact nonthermal radio source, Sgr A\*, which has been identified with the massive black hole ( $4 \times 10^6 M_{\odot}$ ) at the heart of the Galaxy. Exquisite images taken with the new generation of adaptive optics (AO) instrumentation (by groups at Keck Observatory, led by Andrea Ghez of UCLA, and at the European Southern Observatory, led by Reinhard Genzel) have at long last observed direct accretion activity at the location of Sgr A\* in the near infrared. Presumably this activity is due to stellar or gas infall onto the black hole. The enclosed mass within one parsec is dominated by the black hole, but on scales larger than a few parsecs, the stars begin to take over. The present gas content of the Galactic Center is rather low, a few times  $10^4 M_{\odot}$  in molecular material in the circumnuclear ring, whose inner edge is located roughly at 2 parsecs.

Perhaps one of the most difficult questions remaining in the study of the Galactic Center is how stars form in this dense environment. The tidal forces are so extreme due to the black hole (on the smallest scales) and due to the black hole plus stellar mass on parsec scales, that the molecular density required to collapse gravitationally is thousands of times greater than presently observed. And yet, stars do form. In the 1990s, it was recognized that strong compact emission in the lines of HeI and Br gamma were due to evolved massive stars of a few million years in age



Hertzsprung-Russell diagram for the Galactic Center stars (filled squares). Solar metallicity isochrones for ages of 10 million years, 100 million years, 1 billion years, 5 billion years, and 12 billion years are plotted as alternating dotted and solid lines. No isochrones reach the coolest stars, although the solar metallicity isochrones extend to cooler temperatures and provide a better fit than lower metallicity isochrones. All the Galactic Center stars are AGB stars, a consequence of the selection criteria. The horizontal line segment at  $M_{bol} = -7.2$  in each panel indicates the approximate observed luminosity above which only supergiants lie. The Galactic Center stars analyzed at high-spectral resolution by Carr et al. (2000) and Ramirez et al. (2000) are plotted as filled circles.

(see e.g., Krabbe et al. 1991, *ApJ*, 382, L19). Recent AO imaging by the ESO group has detected perhaps lower-mass companions to this activity, and the UCLA group has identified one of the individual stars that orbits the black hole as a main sequence OB star.

Ignoring the apparent difficulties faced by stars during formation, we can take their existence for granted and step back to ask what is the history of star formation in the central few parsecs? It is the cool stellar population that dominates the integrated light at the Galactic Center at

near-infrared wavelengths. The many bright asymptotic giant branch (AGB) stars and M supergiants are excellent tracers of the history of star formation there. There have been many studies of the late-type population at the Galactic Center, but our group has recently completed the first detailed calculation of the star formation history, using advances in stellar models and analysis techniques (see Blum et al. 2003, *ApJ*, 597, 323) along with H-band and K-band spectroscopy obtained with the OSIRIS near-infrared spectrometer at the CTIO Blanco 4-m telescope in Chile.

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## *Star Formation History continued*

Using a sample of about 80 luminous AGB and M supergiant stars in the central 4 parsecs, we have transformed the observed brightnesses to bolometric luminosities and, along with effective temperatures derived from the spectra, have placed them in the Hertzsprung-Russell diagram (see figure). Using a maximum likelihood technique like those used successfully in deriving star formation histories from Hubble Space Telescope color-magnitude diagrams, we computed the star formation history in the Galactic Center.

The sample is relatively small, and thus the models are not unique, but several conclusions can be made. The bulk of the stellar mass in the Galactic Center is old. Approximately 75% of the total mass formed in stars in the Galactic

Center over its history is more than 5 billion years old. The star formation rate is variable, being somewhat more active in the recent past than at the current time and with some evidence that an intermediate age burst (a few billion years) may have occurred at the same time as a similar age burst in the larger inner Galaxy region. This suggests possible connections between the inner Galaxy and its nucleus and events, which may funnel gas from large scales to small. In order to match the estimates of the dynamical mass, the star formation model must have a low mass cutoff in its initial mass function, which might be due to mass segregation effects or to the unique conditions of star formation in the Galactic Center mentioned above. The latter could result in a mass function weighted to more massive stars.

The chemical enrichment picture in the Galactic Center is not clear, but the star formation history analysis gives better fits to the data for models with solar metallicity, even at the oldest ages. There are simply too many stars at very cool temperatures and low luminosity that are not fit by lower metallicity isochrones. Given the limits of the sample, it is possible that an even older, metal-poor component exists but is too faint to have been included. The solar metallicity result is consistent with high-resolution abundance analyses recently completed by the Ohio State group led by Kris Sellgren (see Carr et al. 2000, *ApJ*, 530, 307 and Ramirez et al. 2000, *ApJ*, 537, 205) at least for stars with ages up to about one billion years.

## The Nature of Damped Ly $\alpha$ Absorbers via the Clustering of Lyman Break Galaxies

*Nicolas Bouché (ESO)*

From recent large surveys of galaxies, we know much about the star formation history and the buildup of stellar masses of galaxies as a function of redshift. However, one important question remaining is that if cold gas is being turned into stars, at what rate is the transformation occurring? Our best tracer of cold gas at high redshift is damped Ly $\alpha$  absorbers (DLAs). DLAs are the largest reservoirs of neutral hydrogen at high redshift, but their detailed nature and connection to normal galaxies, as well as their role in the galaxy formation process are unclear.

Wolfe and colleagues have argued that the neutral hydrogen content and kinematics of DLAs are consistent with their origin in massive, gas-rich disks. But theoretical simulations have argued that DLAs can arise from a wider range of structures that are found in overdense

regions, including massive galaxies, their satellites, and filaments.

In a recent study, we have explored the hypothesis that DLAs arise in overdense regions, using the clustering of Lyman break galaxies (LBGs) around DLAs to constrain the dark matter halo mass of DLAs. Basically, if the amplitude of the DLA-LBG cross-correlation is stronger (weaker) than the LBG-LBG auto-correlation, that means that DLA halos are more (less) massive than the halos of LBGs ( $\sim 10^{12} M_{\odot}$ ).

Using the MOSAIC camera on the Mayall 4-m telescope, we imaged three  $z \sim 3$  DLA fields in *UBV* and *I* (see figure). The images cover a wide field (0.34 sq. deg. per field) and include approximately 800 LBGs per field over the redshift range  $2.75 < z < 3.5$ . The wide field of view of the MOSAIC camera was critical. It makes our

observations sensitive to clustering on large scales and provides a control sample of the background surface density of LBGs.

We selected LBGs in a redshift slice using photometric redshift techniques. Preliminary results (Bouché and Lowenthal 2003, *ApJ*, 596, 810) indicated that some DLAs reside in overdense regions: in one of our fields, we see a factor of three enhancement in the density of LBGs within 2.5–5 comoving megaparsecs of the DLA.

The more extensive results of our survey (Bouché and Lowenthal 2004, submitted) show that LBGs are correlated with the absorbers on scales of  $5\text{--}10 h^{-1}$  megaparsecs. The amplitude of the cross-correlation between DLAs and LBGs,  $w_{dg}$ , is  $1.60 \pm 1.3 w_{gg}$  where  $w_{gg}$  is the LBG auto-correlation. This

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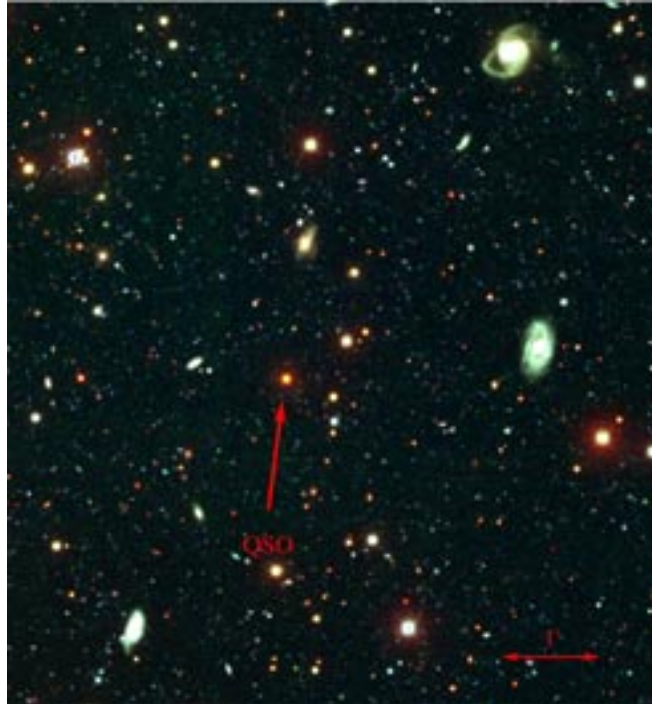
## Damped Ly $\alpha$ Absorbers continued

corresponds to a correlation length of  $r_0=5\pm 4.5h^{-1}$  megaparsecs.

This result is similar to that of Wolfe (1993, *ApJ*, 402, 411) who reported that Ly  $\alpha$  emitting galaxies are clustered near DLAs at  $z\sim 2.6$ . In contrast other, more recent studies did not detect significant clustering (Gawiser et al. 2001, *ApJ*, 563, 628; Adelberger et al. 2003, *ApJ*, 584, 45). Because these recent studies were limited to small angular scales  $<5h^{-1}$  megaparsecs, whereas our study probes larger angular scales ( $>3h^{-1}$  megaparsecs), their results are not inconsistent with ours.

At this point, we cannot determine with greater than 1.5- $\sigma$  confidence whether  $w_{dg}$  is larger than zero, and therefore our ability to constrain the mass of DLA halos is limited. Numerical hydrodynamical simulations suggest that  $w_{dg}=0.7 w_{gg}$  (Bouché et al. 2004, in preparation) and this would imply that DLA halos have masses approximately five times smaller than LBG halos, using the bias prescription of Mo and White (2002, *MNRAS* 336, 112). Our constraint on  $w_{dg}$  is consistent with this prediction within the current observational errors.

The uncertainties on the clustering amplitude improving to the 3- $\sigma$  level, and therefore, the DLA halo mass, will require sampling an additional nine DLA fields—without spectroscopic redshifts. Multi-object spectroscopy of our LBG candidates can halve the current error bars or the number of additional fields required.



The 8 $\times$ 8 arcmin central region of one of the DLA fields studied, toward QSO APM 08279+5255. The QSO appears red in the BVI image due to its redshift ( $z=3.91$ , see the electronic version of the NOAO/NSO Newsletter for a color version of the figure). There are about seven LBGs with  $z_{\text{phot}}\sim z_{\text{DLA}}$  in the portion of the field shown. The full MOSAIC data covers more than 30 $\times$ 30 arcmin, or 40 $\times$ 40 megaparsecs, which enabled us to probe the clustering of LBGs around DLAs on scales of 5 to 10 megaparsecs.

## High-Resolution Thermal Infrared Imaging of SN 1987A

Based on a paper by Patrice Bouchet et al.

The explosion 16 years ago of supernova 1987A at a distance of only 50 kiloparsecs from Earth has given us a unique opportunity to study the evolution of a supernova up close. Recent Gemini mid-infrared (IR) observations of SN 1987A are providing new insights into the birth of supernova remnants and the extent to which dust is produced in supernova events.

Using the Thermal-Region Camera and Spectrograph (T-ReCS) on Gemini South, Patrice Bouchet and collaborators James De Buizer, Nicholas Suntzeff, John Danziger, Thomas Hayward, Charles Telesco, and Christopher Packham imaged SN 1987A on 4 October 2003

(day 6067) as part of the System Verification program for the instrument. With the high angular resolution achieved with T-ReCS on Gemini South (0.3 arcsec at 10  $\mu\text{m}$ ), emission from the equatorial ring was detected and easily resolved (see figure).

The emission from the ring is clumpy, with “hot spots” that are similar to, but not always spatially coincident with, clumps seen in optical emission lines and at X-ray and radio wavelengths. The T-ReCS result confirms the ISOCAM discovery by Fischera and Tuffs that the mid-IR emission is not concentrated in the debris. Bouchet and colleagues interpret the emission as arising from dust that is heated by shocks. Since it is unlikely that much dust has formed in

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## High-Resolution Thermal Infrared Imaging continued

the outer, metal-poor region of the ejecta that is currently interacting with the ring, Bouchet and colleagues suggest that preexisting dust in the surrounding circumstellar envelope is responsible for the emission.

Also detected in the T-ReCS image is weak, spatially unresolved emission from the center of the ring at the 0.32 mJy level. This is interpreted as emission from dust in the supernova ejecta itself. The faint emission is likely to be the remnant dust emission that has been the primary cooling process for the thermalized energy produced by the radioactive nuclides synthesized in the supernova explosion.

With the gradual fading of the emission from the ejecta, SN 1987A had become increasingly difficult to study in the thermal IR. As a result, the thermal IR emission from SN 1987A has been detected only a few times in the last five years. In addition to the Gemini observations, other thermal IR measurements have been made by ISOCAM on the ISO satellite and with OSCIR at Cerro Tololo Inter-American Observatory.

The 0.32 mJy flux density of the central emission feature is consistent with an exponential decline in the 10  $\mu\text{m}$  flux density with time from day 2200 to 6000. This suggests that the much brighter emission from the ring (which is approximately 20 times brighter than the central point source) is a new feature that developed around day 4000 or sometime thereafter.

Such observations of SN 1987A and other supernovae have the potential to address directly the issue of whether supernovae are a significant source of dust, for example, as compared to dust production by winds from supergiants and AGB stars. While various indirect arguments suggest that dust production in supernovae is efficient,

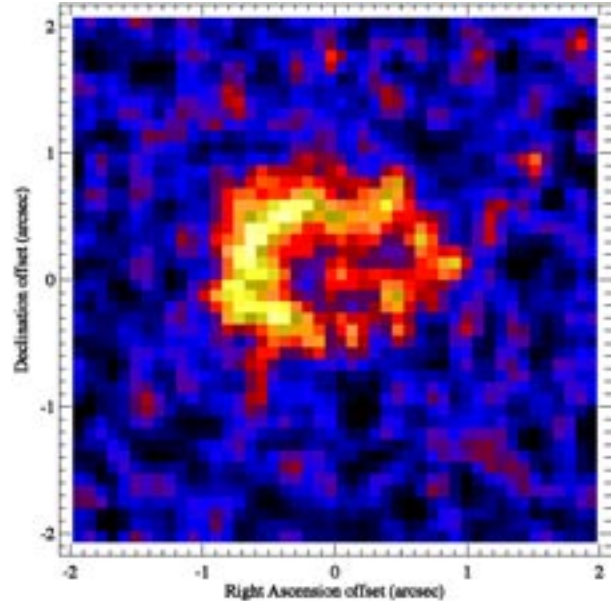


Image of SN 1987A obtained on 4 October 2003, showing the bright equatorial ring and fainter central point source. These results demonstrate the high angular resolution achieved with T-ReCS on Gemini South.

it may be relatively difficult for dust to survive both the intense extreme ultraviolet radiation field in the supernova environment as well as the shocks that are produced as the outflowing material encounters the surrounding medium.

The Gemini observations demonstrate that dust condensates in the SN 1987A ejecta have survived the 16 years since the outburst. Further observations over a wider range of wavelengths are required to measure the mass of the dust that has been produced.

## NOAO at the January AAS Meeting

### A New Titleholder for Most Massive Star?

A 17-member team of astronomers and graduate students led by Steve Eikenberry (University of Florida) have identified a potential new record holder for the most massive star discovered to date.

In their paper, described at the January 2004 AAS meeting and recently submitted to the *Astrophysical Journal*, Eikenberry's team concluded that the luminous blue variable LBV 1806-20 is at least as luminous as the previous record holder, the "Pistol star" (5–6 million  $L_{\odot}$ ), and is perhaps as luminous as 40 million  $L_{\odot}$ , making it potentially the most massive star known. Located 15 kiloparsecs away on the other side of the Galaxy, LBV 1806-20 is highly extinguished and consequently best studied at infrared wavelengths.

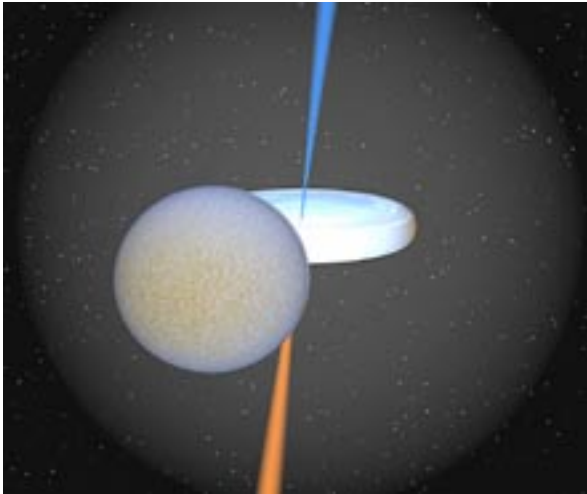
In order to estimate the luminosity of the object, Eikenberry's team used the CTIO Blanco 4-m telescope combined with previous millimeter observations to measure the temperature, extinction, and distance to LBV 1806-20. They also carried out speckle imaging at the Palomar 200-inch telescope. The high angular resolution observations demonstrated that LBV 1806-20 is not a stellar cluster but rather a single or binary star system.

Simple Eddington luminosity arguments suggest a total (single or binary) mass of  $>150 M_{\odot}$  for the object. If the object is a single star, it is substantially more massive than the upper mass limit of approximately  $120 M_{\odot}$  predicted by current theories of star formation.

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NOAO at the January AAS continued



A computer-generated image of the X-ray binary SS 433, produced using software written by Robert Hynes of the University of Texas at Austin.

**The Mass Donor Star in SS 433 Revealed**

Although the X-ray binary SS 433 was made famous 26 years ago when astronomers discovered that the system emits gas jets moving at about one quarter the speed of light, the mass donor component of the system has eluded direct observational study, until now.

In order to detect the donor star, a team of astronomers led by Todd Hillwig of Georgia State University waited for the most opportune moment to observe the system: when the donor star eclipses the extended disk surrounding its unseen companion and at the disk precessional phase when the star lies above the disk. This configuration occurs only twice a year.

As described by the research team at the January AAS meeting, moderate-resolution spectroscopy of SS 433 carried out with the 4-m Mayall telescope on 2 October 2003 revealed the donor star to be an A supergiant. The variation in the strength and velocity shift of the A-star spectrum is consistent with this interpretation. The radial velocity variations imply a mass of  $\sim 11 M_{\odot}$  for the donor star and  $\sim 3 M_{\odot}$  for the unseen companion and its disk, suggesting that the companion is a low-mass stellar black hole. Hillwig and collaborators are planning follow-up

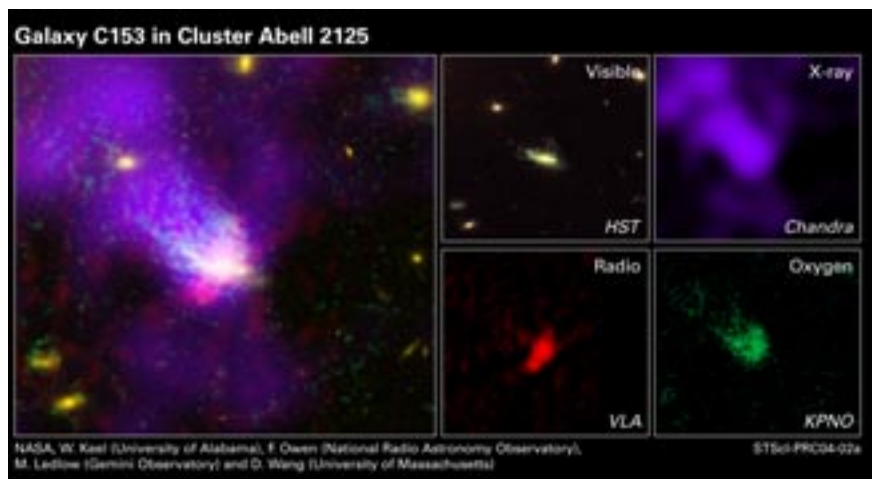
Gemini observations in order to refine their estimate of the component masses.

**A Galaxy Takes the Plunge** (see cover photo)

The close encounter approximately 100 million years ago of major merging subsystems in the well-known cluster Abell 2125 is thought to have thrown cluster member C153 onto an infall trajectory into the dense cluster core. Recent observations of induced star formation and gas stripping from C153 provide insight into how cluster-level mergers may affect the evolutionary histories of galaxies.

The transformation of C153, as a consequence of its headlong plunge, was described by astronomers William Keel, Frazer Owen, Michael Ledlow, and Daniel Wang in a presentation at the January AAS meeting. Imaging with the Mosaic camera on the Mayall 4-m telescope revealed a tail of ionized gas, detected in [OII] emission, that extends more than 70 kiloparsecs toward the cluster core. The tail is coincident with a soft X-ray feature detected with the Chandra X-ray Observatory.

The optical morphology of C153, as measured with HST WFPC2, is clumpy, showing irregular dust features as well as multiple sites of star formation embedded within the envelope of the ionized gas tail. Further evidence that the gaseous component of the galaxy has been disturbed comes from optical spectroscopy obtained with Gemini North. GMOS spectroscopy shows that the gas kinematics are decoupled from the stellar kinematics and possess multiple gas velocity systems, including counter-rotating components. The optical spectroscopy also shows that the most recent burst of star formation in the galaxy occurred approximately 100 million years ago. The timing of the burst strongly suggests that the burst was triggered by the passage of C153 through the dense cluster core.



Composite image showing galaxy C153 as it travels through the cluster Abell 2125. The separate images were taken in X-ray (with Chandra), radio (by VLA), and visible (with HST) wavelengths, as well as the green light of singly-ionized oxygen at the KPNO Mayall 4-meter telescope.