

# Infrared Spectroscopy of a Massive Obscured Star Cluster in NGC 4038/4039 with NIRSPEC

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## 1 Infrared Spectroscopy of Extragalactic Star-forming Clusters

Star formation in massive clusters appears to be a primary mode of star formation in starburst systems. IR spectroscopy has a vital role to play in studying this mode of star formation because star formation occurs in dusty regions and is highly obscured. IR spectroscopy constrains stellar populations: strong 2.3  $\mu\text{m}$  CO bands trace red supergiants in populations older than  $\simeq 10^7$  yr; Wolf-Rayet stars have strong, broad emission lines in the near-IR; the underlying giants are traced by NaI, MgI, CaI, SiI, FeI & CO. H recombination lines, e.g., Br $\gamma$ , measure the Lyman continuum flux and can be used to measure  $A_V$ , and H<sub>2</sub> emission traces PDRs and shocks.

## 2 NIRSPEC Observations

NIRSPEC is a new facility infrared (0.95 - 5.6  $\mu\text{m}$ ) spectrometer for the Keck-II telescope, commissioned during April through July, 1999 (McLean et al. 1998). It has a cross-dispersed cryogenic echelle with  $R = 25,000$ , and a low resolution mode with  $R = 2000$ . The spectrometer detector is a  $1024 \times 1024$  InSb ALADDIN focal plane array, and the IR slit-viewing camera detector is a  $256 \times 256$  HgCdTe PICNIC array.

NGC 4038/4039, (the Antennae Galaxy) was observed with NIRSPEC during the June 1999 commissioning run. Slit-viewing camera (SCAM) images at 2  $\mu\text{m}$  reveal that the mid-IR ISO peak is a bright ( $K = 14.6$ ) compact star cluster with  $M_K = -17.7$ . This cluster is associated with a faint ( $V = 22.8$ ) red ( $V - I = 3.3$ ) source visible with HST. We obtained low resolution ( $R \simeq 1500$ )  $\lambda = 2.0 - 2.4 \mu\text{m}$  spectra through a  $0.''57 \times 42''$  slit located on the obscured star cluster and the nucleus of NGC 4039. The total integration time on source was 2100 s.

## 3 Massive Star Cluster

The cluster spectrum is characterized by strong, extended emission lines and a continuum (detected with  $SNR \simeq 30$ ) dominated by the light of hot blue stars and dust. The H<sub>2</sub> emission indicates that the cluster ionizes and photodissociates the local ISM on kpc scales.

The cluster has  $V - K = 8.2$ , and assuming an intrinsic color of  $(V - K)_0 = 0 - 1$  implies  $A_V = 8 - 9$  mag. Thus  $M_K(0) = -18.6$ , implying that it is a young cluster with mass  $M = 11 \times 10^6 M_\odot$  for a Salpeter IMF extending from 1 to 100  $M_\odot$  (Leitherer et al. 1999). The strong Br $\gamma$  emission

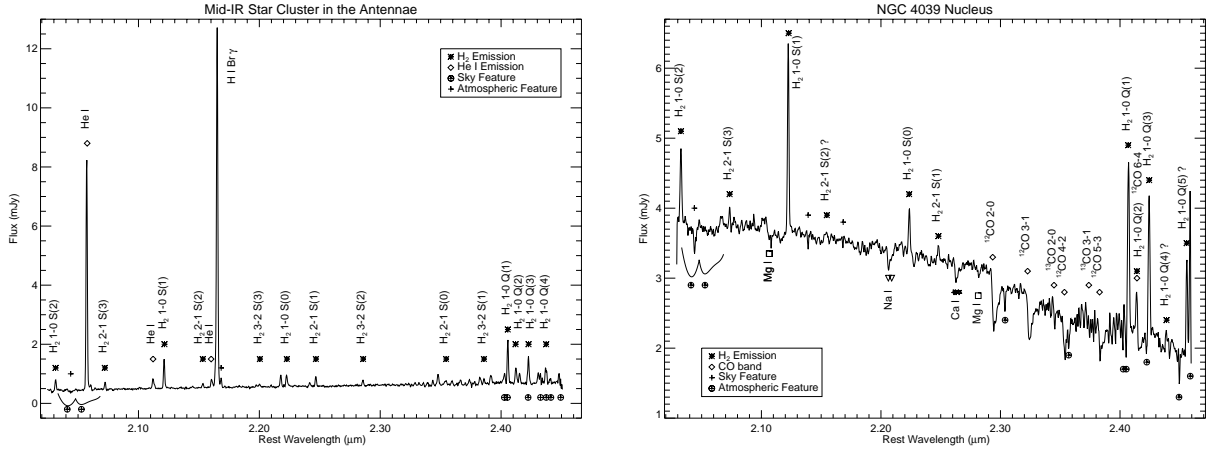


Figure 1: NIRSPEC spectra of ISO mid-IR star cluster and NGC 4039 nucleus, corrected for atmosphere.

from the cluster corresponds to a Lyman continuum flux of  $Q(H^+) = 2.1 \times 10^{53} \gamma s^{-1}$ , and provides an alternative estimate of the number of OB stars present. For an instantaneous starburst ( $t < 3$  Myr) the observed Br $\gamma$  flux requires  $4.3 \times 10^6 M_\odot$ , which is consistent with the mass inferred from the cluster brightness.

The spectrum shows evidence for almost pure UV fluorescence excited by FUV radiation from the O & B stars; the strong, vibrationally excited 1-0, 2-1, & 3-2 H<sub>2</sub> emission has  $T_{vib} \simeq 6000$  K. Both Br $\gamma$  and H<sub>2</sub> lines are extended over  $\simeq 300 - 400$  pc, so a significant fraction of the Lyman continuum and FUV (912-1108Å) light escapes from the cluster and illuminates the local ISM. The lack of a Pfund discontinuity at 2.28  $\mu$ m indicates that nebular free-free and bound-free continuum are insignificant in the cluster. The rising continuum through the K-band indicates that hot dust emission is excited by the OB stars.

The cluster shows no CO overtone absorption at 2.3  $\mu$ m, and no photospheric metal absorption lines. Thus red supergiants and other cool stars do not contribute significantly to the 2  $\mu$ m light.

## 4 NGC 4039 Nucleus

The spectrum of the nucleus of NGC 4039 is marked by strong stellar continuum and bright, extended H<sub>2</sub> emission. Strong photospheric Mg I, Na I, Ca I absorption and CO  $\Delta v = 2$  bands indicate that the continuum is dominated by old giants. The CO band head is stronger than that of a M2III, suggesting some contribution from red supergiants. The absence of Br $\gamma$  emission implies that no O stars are present.

Spatially extended, collisionally excited H<sub>2</sub> emission is present in the nucleus, with no evidence for UV fluorescence. The molecular gas may be excited by SNR shocks from the last generation of nuclear star formation. Star formation is currently extinct in the nucleus, but its long-term effects are still detectable.

## 5 References

- Leitherer, C., et al. 1999, to appear in ApJ  
 McLean, I. S., et al. 1998, SPIE 3354, 566  
 Mirabel, I. F., et al. 1998, AA 333, L1