The Central Kiloparsec of Starbursts and AGN: The La Palma Connection
ASP Conference Series, Vol. 249, 2001
J. H. Knapen, J. E. Beckman, I. Shlosman, and T. J. Mahoney, eds.

The Ages of Circumnuclear Starbursts from Near-IR Spectroscopy: Bushfires or Mexican Wave?

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Abstract. We have obtained K-band spectra with CGS4 on UKIRT for circumnuclear star-forming regions in NGC 4321, NGC 2903, and NGC 7469. A comparison of the equivalent widths of Brγ emission and CO absorption with starburst models in the literature allows us to simultaneously determine the age distribution and burst decay timescales around each ring. We find that the majority of the star-forming regions are rapidly decaying bursts with ages between 8 and 10 million years, but that only NGC 4321 displays a clear age sequence. We discuss the implications of these results for the triggering and evolution of circumnuclear star formation.

1. Introduction

Circumnuclear rings of star formation appear to be quite a common feature in barred spiral galaxies. The compact "knots" of star formation within them are thought to be miniature versions of starburst galaxies and can consume prodigious amounts of gas (potentially starving a central black hole of fuel in the process). The gravitational torques induced by the bar provide a natural mechanism for "funneling" more gas into the central regions to sustain the circumnuclear star formation (CSF) and/or the AGN. However, the actual mechanism which initiates CSF in the ring is not well understood.

To study this problem, we have commenced a program of age-dating CSF regions, to see if the age distribution is random, or ordered. If, for instance, CSF simply takes place whenever the local gas density exceeds some critical threshold density (the "bushfire" scenario), then one might expect a fairly chaotic age pattern around the ring. If, on the other hand, star formation relies upon some sort of trigger mechanism, such as might be supplied by a spiral density wave, then a more organized, sequential age pattern should result (the "Mexican Wave" scenario, known locally as *La Ola*). Of course, a number of factors may conspire to disrupt any organized CSF (see Elmegreen, this volume, p. 493), but only a detailed investigation of the age distribution of CSF in a variety of galaxy nuclei will reveal which is the dominant effect.

2. Starburst Clocks

One way in which to determine the time since a burst of star formation began is to use the equivalent width of a hydrogen recombination line, such as Hα in the optical, or Brγ in the near infrared. As fig. 89 of Leitherer et al. (1999; hereafter SB99) shows, the equivalent width of the Brγ line starts off at $\sim$ 500 Å at 1 Myr after the onset of an instantaneous burst and remains there until $\sim$ 3 Myr, after which the increasing number of hot, blue supergiants evolving to cool, red supergiants causes a rapid drop to $<$ 1 Å after 10 Myr (the exact values depend to some extent on the ambient gas metallicity, and the form of the stellar initial mass function assumed). However, as fig. 90 of SB99 shows, even continuous star formation at a rate of 1 $M_{\odot}$ yr^{-1} yields a not-too-dissimilar behavior, although the equivalent width declines much more slowly. Thus, any given H line equivalent width does not uniquely determine the age, unless the burst duration is already known.

What is needed is a second diagnostic, which also varies rapidly in this 3–10 Myr period, and would ideally be close in wavelength to the first diagnostic, so that the two can be measured simultaneously and with minimum differential extinction. As figs. 101 and 102 of SB99 indicate, the 2.29 μm absorption bands of CO exhibit just this behavior (except that the CO strength increases with time, as more and more red supergiants appear), and they can generally be observed simultaneously with the Brγ line at 2.16 μm. Thus, knowledge of both the Brγ and CO equivalent widths in a CSF region ought to tightly constrain both the time since the onset of the burst, as well as its duration, as we now demonstrate for three different galaxies (see also Puxley, Doyon, & Ward 1997 and Vanzi, Alonso-Herrero, & Rieke 1998).

3. Observational Results

3.1. NGC 4321 (M100)

M100 is the brightest spiral galaxy in the Virgo Cluster and has a grand-design spiral pattern that persists almost to the very nucleus. Ryder & Knapen (1999) obtained near-IR images with seeing better than 0.″4 of the circumnuclear region and identified at least 40 compact "knots" which they showed to be CSF regions. They followed this up with low resolution ($R \sim 450$) long-slit spectroscopy in the K band using CGS4 on UKIRT for 16 of these knots (Ryder, Knapen, & Takamiya 2001), as shown in Figure 1.

Also in Fig. 1, we compare the observed line strengths for the 16 CSF regions which could be measured with the evolutionary track predictions of Puxley et

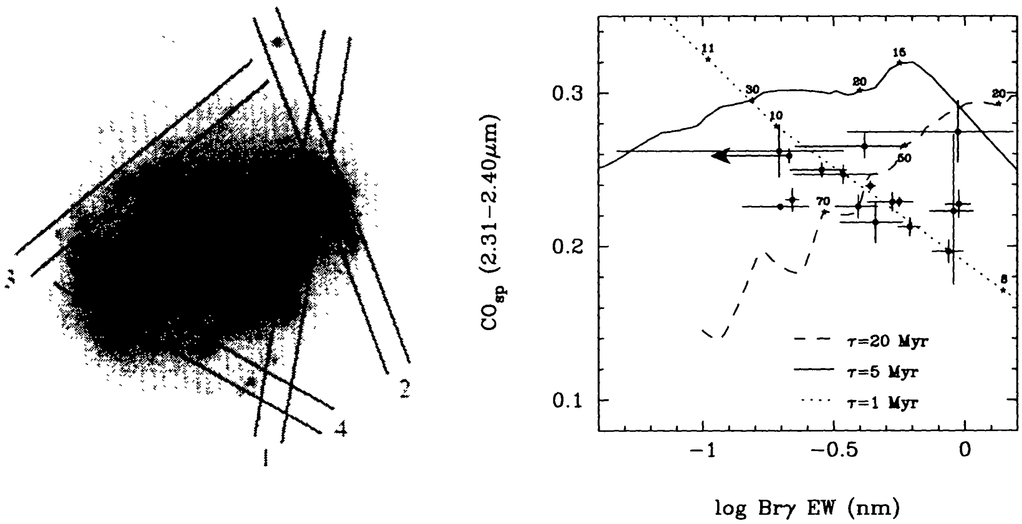

Figure 1. *Left:* A high-resolution K-band image of the circumnuclear region of M100, obtained in 1998 February by Ryder & Knapen (1999) with IRCAM3 on the United Kingdom Infrared Telescope (UKIRT). The four slit positions observed subsequently with CGS4 on UKIRT are labeled. *Right:* The CO spectroscopic index measured for each independent CSF region is plotted against its Brγ equivalent width, along with the model predictions for three starbursts with an exponential decay rate τ from Puxley et al. (1997).

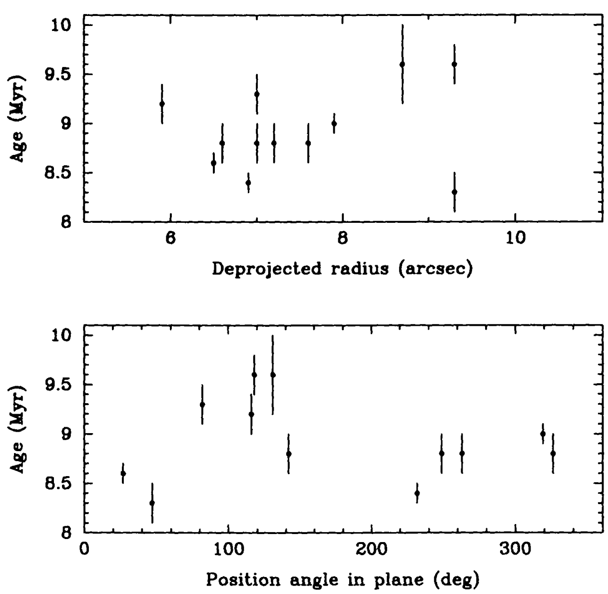

Figure 2. The derived ages for the 12 knots in M100 which appear to best follow the evolutionary trend of the $\tau = 1$ Myr burst track in Fig. 1, plotted against deprojected radius (*top*) and azimuth (*bottom*) in the disk of M100. The zero-point of the position angle scale corresponds to the kinematical major axis $\phi = 153°$ (roughly halfway between knots 20 and 37 in Fig. 1), and position angle increases going counter-clockwise.

al. (1997) for a starburst decaying exponentially at a rate $\tau = 1$, 5, or 20 Myr. The SB99 evolutionary tracks are similar, but are available only for the two extremes of an instantaneous burst ($\tau \ll 1$ Myr), and continuous star formation ($\tau = \infty$). Clearly, the bulk of the knots are consistent with a quasi-instantaneous $\tau = 1$ Myr burst, and ages between 8 and 10 Myr, which could not have been deduced on the basis of photometry alone.

Once the burst duration is known, the position of each CSF region along an evolutionary track uniquely defines an age. In Fig. 2, we plot the derived ages for each one against its radial distance and azimuthal angle in the plane of the disk of M100. Although the sampling is still somewhat sparse, the age distribution is clearly not random. The CSF regions at either end of the bar are all of similar age (8.8 Myr). The oldest regions are found just south of the western end of the bar, while the youngest are all along the bar minor axis. There are also hints of a radial age gradient among the CSF regions. These results provide the strongest evidence yet that, at least for the case of M100, CSF is being sequentially triggered. However, the observed age spread is much larger than can easily be accounted for by the timescale of most proposed propagation mechanisms, such as the bar pattern speed, gas streaming motions, or a spiral density wave.

3.2. NGC 2903

Our second spectroscopic target is the "hotspot" galaxy NGC 2903 (Alonso-Herrero, Ryder, & Knapen 2001). Figure 3 shows a K-band image of the nuclear region of this galaxy, obtained with the adaptive-optics system PUEO on the Canada–France–Hawaii Telescope (CFHT), with a resolution of $0\farcs25$. Spectroscopic results for many of these hotspots, obtained in the same manner as for NGC 4321, are also shown.

Owing to the compactness of the CSF region of NGC 2903 as compared to that of NGC 4321, it is more difficult to resolve the spectra of individual hotspots. Spectra of the nuclear region "C" are consistent with continuous star formation. The southern-most hotspots appear to be 1 Myr or so younger than those to the north and northeast. Nevertheless, the sparse sampling achieved so far, and the inability to separate neighboring hotspots, limits what we can conclude in this particular case. Alonso-Herrero et al. (2001) observed that the Paα emission from H II regions in NGC 2903 is already significantly displaced from the K-band stellar emission, meaning that the current star formation is no longer spatially coincident with the young clusters. Since all the starburst models assume that star formation stays fixed, our derived ages may be in error. However, since we target the K-band sources, we would expect to miss some of the Paα emission, causing most of our sources to fall below, and to the left of the evolutionary tracks in Figure 3. In fact, the opposite tends to be the case, indicating that this is not as serious an effect as one might have feared.

3.3. NGC 7469

An even greater observational challenge is presented by the Seyfert 1.2 galaxy NGC 7469. The circumnuclear ring is just $3''$ in diameter and surrounds a very bright nuclear point source. By carefully positioning the $0\farcs6$ CGS4 slit at the locations marked in Fig. 4, we have been able to obtain spectra around the ring

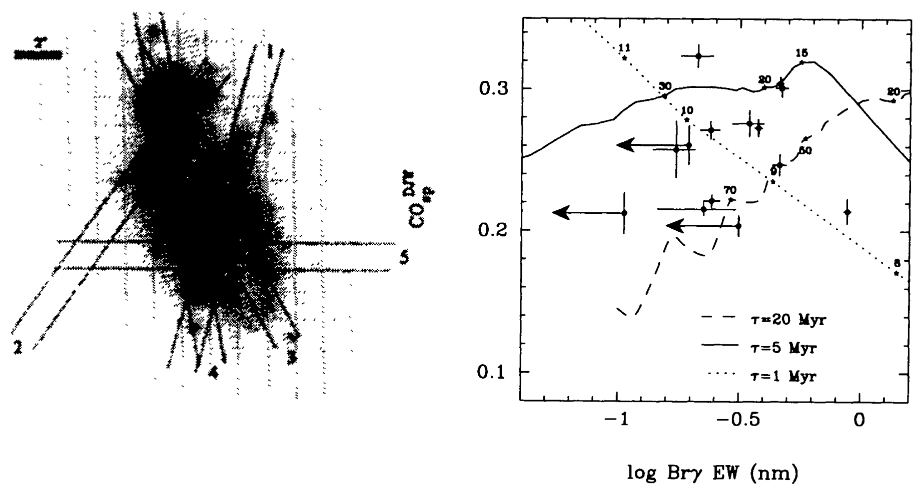

Figure 3. *Left:* CGS4 slit positions, superimposed on a CFHT K-band adaptive-optics image of the hotspot nucleus of NGC 2903. *Right:* Observed line strengths for the CSF regions on the same evolutionary tracks as plotted in Figure 1.

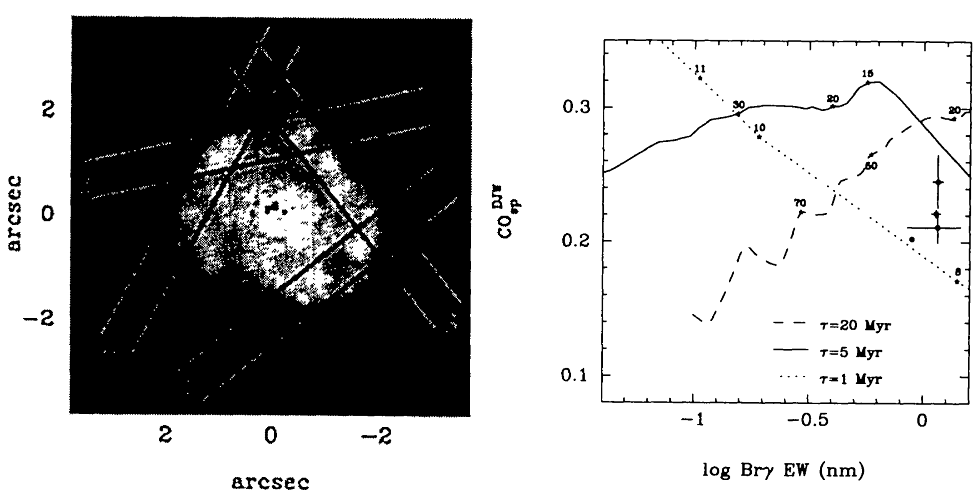

Figure 4. *Left:* CGS4 slit positions, superimposed on a *HST*/NICMOS F110W (J-band) image of the nucleus of NGC 7469, from which the bright nuclear point source has been removed in order to highlight the circumnuclear ring. *Right:* Observed line strengths at the four slit positions on the same evolutionary tracks as plotted in Figure 1.

with $< 2\%$ contamination from the bright Seyfert nucleus. Although it is still not possible to extract spectra for individual CSF regions, we are able to derive (luminosity-weighted) line fluxes at four distinct locations around the ring, and these results are presented along with the usual evolutionary tracks in Figure 4. All four slit positions have virtually the same Brγ equivalent width, but a spread in the CO spectroscopic index implies that the burst decay timescale is shortest ($\tau = 1$ Myr) on the eastern side of the ring, and steadily increases going counter-clockwise around the ring. Thus, although star formation in the circumnuclear ring of NGC 7469 may have been initiated in a single burst, the star formation history is not the same everywhere in the ring.

4. Conclusions and Caveats

We have presented the first results from a near-IR spectroscopic survey of the age distribution around circumnuclear star-forming rings in three spiral galaxies. Even at low spectral resolution ($R < 1000$), age differences as small as 0.2 Myr are detectable, but sub-arcsecond imaging and slit widths are needed to separate individual hotspots. The nucleus of NGC 4321 shows the clearest evidence yet for sequential azimuthal (and perhaps radial) age sequences, consistent with the "Mexican Wave" hypothesis. The age distribution appears to be more stochastic in NGC 2903, while the CSF regions around NGC 7469 are effectively coeval, and differ mainly in the rate at which the starburst has decayed.

Our conclusions must be tempered by some notes of caution however. The behavior of the CO spectroscopic index in individual stars as a function of temperature and surface gravity are still not well understood (Origlia & Oliva 2000; Ryder et al. 2001), casting some doubt on the applicability of the starburst models (but see also Ivanov, this volume, 522). As mentioned for NGC 2903, the static nature of the models compared with the rapid propagation of new star formation may also be an issue. Last but not least, our technique of long-slit spectroscopy which targets compact K-band sources is inherently biased towards selecting bursts having ages 5 Myr $< t <$ 25 Myr, and may miss the youngest (pure emission line) objects. The increasing availability of near-IR Integral Field Units (e.g., UIST, CIRPASS) should go some way towards redressing this.

References

Alonso-Herrero, A., Ryder, S. D., & Knapen, J. H. 2001, MNRAS, 322, 757

Leitherer, C., et al. 1999, ApJS, 123, 3 (SB99)

Origlia, L., & Oliva, E. 2000, A&A, 357, 61

Puxley, P. J., Doyon R., & Ward M. J. 1997, ApJ, 476, 120

Ryder, S. D., & Knapen J. H. 1999, MNRAS, 302, L7

Ryder, S. D., Knapen J. H., & Takamiya, M. 2001, MNRAS, 323, 663

Vanzi, L., Alonso-Herrero, A., & Rieke, G. H. 1998, ApJ, 504, 93

Discussion

Kenney: Could it be that the slightly older ages you derive for the clusters near the ends of the nuclear bar of M100 are affected by a contribution of light in your aperture from the older stars of the bar? (There would be a greater contribution from the "background" stars near the bar end than along the bar minor axis.)

Ryder: Certainly, inadequate removal of background stellar light will tend to deepen the CO bands, leading to an overestimate of the age. However, getting spectra of even the bright K-band knots in M100 is difficult enough with 4 m telescopes, and in fact we detect almost no stellar continuum outside the knots.

Ivanov: What is the extinction towards these clusters?

Ryder: Based on the observed $(I-K)$ color excesses, we derive visual extinctions A_V ranging from 4.2 mag for those knots within the dust lanes, to 0.1 mag for those well outside.

Stuart Ryder (right) talking to Samantha Rix (left).