Observations of the globular cluster M15 with the AOB and a Fabry-Perot

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Since 1994 we have been using the good seeing of the CFHT to probe the stellar kinematics and distribution of mass near the centers of globular clusters, particularly those with collapsed cores (Gebhardt et al. 1997). We use the Rutgers Fabry-Perot narrow etalon to take a sequence of images stepped in wavelength across a strong absorption line. Stellar photometry of these images with DAOPHOT (Stetson 1997) allows us to build up a short section of spectrum for every resolved star. Fitting a line profile to each spectrum yields the radial velocity.

In the centers of dense clusters our sample sizes have been limited by crowding rather than photons. With the ready availability of bright guide stars, this program is well-suited to the CFHT AOB. The only potential problem is that we need good photometry – about 2% – to obtain accurate velocities and some published reports suggest that this is difficult to obtain with adaptive optics systems (Roberts et al. 1997, Esslinger & Edmunds 1998). A further difficulty is the low Strehl ratio achievable at the wavelengths where our etalon works – we obtained 0.01 to 0.06 in excellent conditions – which complicates the estimation of the point-spread function (PSF). We focus in this article on our experience performing stellar photometry in images with small Strehl ratios and argue that photometry accurate to a few percent is possible.

In consultation with the CFHT staff, we chose to place our etalon in the f/40 converging beam behind the AOB focal expander. The STIS2 CCD yielded 0.031 arcsec pixels and a 63 arcsec field of view. However, the wavelength resolution of the etalon was degraded by the tilting of the converging beams away from the center of the field (i.e., the AOB optics are not telecentric) and this limited us to a region about 20 arcsec across. Because our primary targets were the centers of clusters, this limited field did not significantly compromise our scientific goals. At the center of the field, the converging beam caused a negligible degradation of the 2.0 Angstrom wavelength resolution.

The coatings of the Rutgers etalon allowed us to work at the 8542 Angstrom Ca triplet line. Choosing a line as far to the red as possible maximized the gain in angular resolution from the adaptive optics. We employed our own filter with a 30 Angstrom FWHM to isolate the correct etalon order. A dichroic in the AOB sent the I band light to the CCD and all other wavelengths to the wavefront sensor.

Our four night run in June 1998 was preceded by an engineering night. Hard work by the CFHT staff meant that we were observing by midnight of the engineering night. That was fortunate, as that night yielded our best seeing, with some of the 15 minute exposures of M15 having stars with a full width at half maximum (FWHM) of 0.1 arcsec. This night and the next were clear, while the following three had varying amounts of cirrus. Stellar FWHMs were around 0.1 arcsec on the engineering night, 0.1-0.2 arcsec on the second and fifth nights and 0.3-0.4 arcsec on the third and fourth nights. We obtained 24 15-minute exposures of M15, our primary target, and 13-14 exposures each for M13, M80, and M50. The data for M15 and a radial velocity standard observed in twilight are reduced and discussed here. For more details, see Gebhardt et al. (1999).

Figure 1 compares the average of our four best M15 frames with the R+U+B+V color composite Hubble Space Telescope image of Guhathakurta et al. (1996). Both images show the central 9x9 arcsec of the cluster and are displayed using a logarithmic mapping of intensity values to show both bright and faint stars. Our image has been rotated to the same orientation as that from the HST and the diagonal dark line is a bad column. The cores of the stars in the AOB image are nearly as sharp as those in the HST image. The AOB image does not go as deep, at least in part because the 2 Angstrom bandpass meant that we collected about five times fewer photons despite using a longer exposure time and a larger telescope.

The star used for the wavefront correction of the M15 images was AC3, with V=13.5 and B-V=1.1 (Auriere & Cordoni 1981). It is 6.7 arcsec from the cluster center and out of the field of figure 1 to the right. Figure 2 shows the radial profile of this star in the M15 images, plotted with both linear-linear and log-linear axes. These profiles have all been normalized to the same arbitrary central intensity. Also shown as dashed lines are the diffraction-limited and uncorrected stellar profiles (with FWHMs of 0.05 and 0.5 arcsec, respectively). The wide range in the profile shapes reflects the 0.01 to 0.06 range in Strehl ratios for these images. However, this plot and a similar one for images of a bright radial velocity standard star suggest that the corrected stellar profiles have a sharp, nearly diffraction limited core surrounded by an envelope resembling the uncorrected stellar profile. Only about 10% of the light is in the sharp core even for the images with the highest Strehl ratio. Clearly, one challenge for obtaining accurate photometry is measuring the extended PSF profile with sufficient accuracy to determine the aperture correction between the amount of light in the inner, high signal-to-noise (S/N), portion of the profile and the total amount of light.

We determine both the aperture corrections and our photometric uncertainties by fitting line profiles to our stellar spectra. The fitted profiles are based on our knowledge of the instrumental profile. Stars with previously-measured velocities provide the information to determine a
single multiplicative correction to all of the fluxes measured in each frame, thus compensating for changing aperture corrections and non-photometric conditions together. The photometric accuracy achieved by this procedure for the M15 AOB data is indicated in figure 3, which shows the root-mean-square (RMS) scatter of the photometry about the fitted line profiles calculated using the 40 brightest stars. Each point in the plot is the RMS scatter of the photometry from a single frame, plotted versus the FWHM of AC3 in that frame. The RMSs range from 2% to 4.5% and are perhaps somewhat larger for the frames with worse seeing. We usually achieve an average RMS of about 2% with our Fabry-Perot data. The increased uncertainty in the AOB spectra probably results from some combination of the increased photometric errors from the adaptive optics, the small S/N in the 0.03 arcsec pixels when the FWHM was 0.2 arcsec or larger, and the larger uncertainties in the wavelength calibration related to having the etalon in the converging beam. The RMS scatter does not increase with increasing distance from the center of the field, so the variation of the PSF does not contribute to the uncertainty over the 20 arcsec region in which we can obtain velocities.

**Figure 1**: The upper panel is the average of our four best frames of the central 9x9 arcsec of M15. The lower panel is a U+B+V color composite Hubble Space Telescope image of the same region from Guhathakurta et al. (1996). Both images are displayed using a logarithmic mapping of intensity values to show both bright and faint stars.

**Figure 2**: Radial profiles of the star used for wavefront correction in the M15 images. They have all been normalized to the same arbitrary central intensity. The upper panel emphasizes the inner portions of the profiles, while the lower panel emphasizes the outer portions. The dashed lines are the diffraction-limited and uncorrected stellar profiles (with FWHMs of 0.05 and 0.5 arcsec, respectively).

**Figure 3**: The root-mean-square (RMS) scatter of the photometry about the fitted line profiles calculated using the 40 brightest stars. Each point in the plot is the RMS scatter of the photometry from a single frame, plotted versus the FWHM of AC3 in that frame. The average accuracy of our photometry is about 3%.
The frame-to-frame normalizations for photometry obtained with a PSF extending to a radius of 30 pixels imply that flux is lost as the FWHM of AC3 increases. This clearly shows that aperture corrections are still necessary for that PSF radius. The normalizations show much less dependence on seeing when the PSF extends to 50 pixels. A similar story is told by our only sequence of observations taken at the same wavelength. Four consecutive 10s exposures of HD107328 (HR 4695; V=4.96) were taken in twilight on the fourth night. Conditions were mildly non-photometric and the Strehl ratios were about 0.03. The diamonds in figure 4 show the RMS scatter around the average aperture magnitude for apertures with radii between 3 and 150 pixels. The pluses are the uncertainties in the magnitudes expected from photon statistics. The RMS scatter in the magnitudes decreases with increasing aperture size until a radius of 50 pixels, after which it slowly increases. This suggests that changes in the PSF caused by variations in the seeing and wavefront correction have become small by an aperture radius of 50 pixels. The amount of light within this radius is about 87% of that within a radius of 150 pixels for these data.

Successive exposures of a bright star probably produce the smallest possible photometric errors. On the other hand, the scatter in our M15 spectra is probably increased by difficulties in calibration and flattening caused by having the etalon in the converging beam. So our data suggest that photometry accurate to a few percent is possible in the central regions of the AOB field even with Strehl ratios of 0.01 - 0.06. However, the field must contain stars bright enough to determine the PSF to a radius of about 50 pixels (1.5 arcsec -- about three times the uncorrected stellar FWHM and containing about 90% of the total light).

Our AOB data yielded velocities for 107 stars, with 21 of these not being previously measured with our SIS data (Gebhardt et al. 1997). Four new stars were added to the 12 previously measured within a radius of 2 arcsec. The dispersion of these 16 stars is 11.3 ± 2.2 km/s, which is the same as the dispersion out to about 30 arcsec. Of the four stars measured within a radius of 1 arcsec, the one farthest from the mean appears to be variable based on the disagreement of our AOB and SIS velocities. Our AOB data will yield larger increases in the velocity samples for the other three clusters observed, which have been less intensively studied than M15. We also believe that by operating the etalon in collimated light and by changing the binning and exposure times as the seeing degrades from HST-like to simply superb, we could increase the number of new stars in the center of M15 considerably.

References

Roberts, L. C., Jr., ten Brummelaar, T. A., and Mason, B. D. 1997, AAS Meeting 191, #128.01

MosArgus and the feedback process in starburst galaxies

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Abstract

The physics behind the star forming process in galaxies is an active field of research. The threshold mechanism and the type of feedback that is associated with it are among the most controversial issues. Some of these issues are addressed in this paper and a method to gain knowledge about the feedback parameter is proposed. The use of MosArgus 2-D spectroscopy with the BHK Diagram is suggested to infer the timescales of the star formation process and its relationship with the physical properties of starburst galaxies.

Galactic star formation

The star formation process is known to be important in the evolution of a galaxy. However, the coupling between the stars and the gas is not well understood and “recipes” must be used to model this interaction
in galaxy evolution simulations. The work of Schmidt (1959) paved the way for studies of the mechanics of star formation inside galaxies. By studying the solar neighborhood, he determined that the star formation rate and the gas density are related by a power law with the value of the exponent n being between 1 and 3. He suggested to use n=2.

The Schmidt law describes the global trend of star formation properties. Many studies (see Kennicutt 1997 for a review) have attempted to determine the exponent of this law. The values usually ranges from $n = 0.8 - 2.5$. However, this trend is usually close to linear ($n = 1.3-1.4$) for star forming disks but can become highly non-linear for starbursting regions or for regions where the star formation is lower than what is observed in disks. Hence, the inclusion of a stability threshold is necessary to account for the observed deviations from the Schmidt law.

Criteria for stability were introduced for the simple case of an isothermal thin disk of pure gas or of pure stars by Safronov (1960) and Toomre (1964), respectively. These two very similar criteria predict that the disk will be stable if the surface density doesn’t exceed a certain critical value. It is not clear if this density threshold is an universal constant or if it depends on local conditions (see Hunter, Elmegreen & Baker 1998 and references therein).

**Constant or local threshold?**

With a constant density threshold, star formation occurs when the density of the gas reaches a certain value. A good example of such modeling is the work on galaxy structure and evolution with self propagating star formation done by Mueller & Arnett (1976) and Gerola & Seiden (1978) among others (for a good review on this subject see Seiden & Gerola 1982). Such modeling of the star formation properties of a galaxy, along with the thin disk approximation and the input of feedback, reproduces the feathery spiral patterns observed in some galaxies. However, this type of modeling is far from being satisfactory for the bulk of the galactic population.

The local threshold theory dates back to the work of Quirk (1972). He suggested that star formation is a threshold phenomenon that depends on the amount of gas added to the ISM from stellar winds or from infall of gas, and on the threshold density of this gas. The idea was put to the test by Kennicutt (1989) who combined Hα imaging with published HI and CO data of a sample of disk galaxies. His results showed that for most of the sample, the Schmidt law with power 1.3 - 1.5 combined with a local threshold explains qualitatively the radial behavior of the star formation rate. This observation strongly suggests a feedback mechanism in order to stop the star formation from consuming all the available gas. The source of this feedback is not clear. It may come from the gas-stars interaction (star formation efficiency) or it may also be caused by the interaction between the stars and the ISM (SN ejecta, stellar winds, etc...).

More recently, this test was performed on a sample of irregular galaxies by Hunter, Elmegreen & Baker (1998). With a similar analysis, they found that the radial behavior of the star formation rate was incompatible with the local threshold model. In fact, they showed that the surface density of the gas follows the surface density of the stars. They proposed that this correlation could mean that the threshold for star formation is universal and that this may apply to spiral galaxies as well. If the stars follow the gas, this means that the star formation rate is constant with radius over timescales of a Gyr or that there is a feedback mechanism between the old stars and the gas that helps the formation of gas clouds.

### Feedback

Both threshold scenarios lead to feedback considerations. This parameter is poorly understood and is often set ad-hoc in galactic evolution modeling to fit the output of the models to the observations. Clearly, better knowledge of this parameter is required. Constraining the feedback mechanism is not an easy task. It requires knowledge of the timescales of the star formation process and of the physical properties of the ISM where the stellar activity takes place.

Starburst galaxies are ideal objects to study such phenomena. They form highly compact and luminous Star Clusters (SSC) that emit a tremendous amount of photons in all wavebands. Their high luminosity and high ionisation make it possible to perform detailed studies on the star formation timescales as a function of the ISM’s metallicity, electronic temperature and state of ionisation.

**Figure 1: BHK color diagram of the starburst merger Arp 299.** The solid curves are the theoretical models from Leitherer et al. (1999) for a burst of star formation from 0 to 30 Myr at 0.40 solar metallicity without dust emission (left curve) and considering a 0.2 mag increase in K magnitude due to dust emission (right curve). The observed points shown are those brighter than an absolute B magnitude of $-10$ and an absolute K magnitude of $-14$. The observations have been corrected for $E(B-V)=0.16$.

### The star forming process and the ISM

#### 4.1) The BHK Diagram

The BHK diagram method (Figure 1) is used to determine age differences between the different SSC observed inside a starburst galaxy. The possibilities of this method have already been outlined in a previous article (CFHT Bulletin #38; “Arp 299, un super starburst en interaction!”) (see also Figure 2). The method uses the (B-H) vs (H-K) two color diagram with the starburst modeling of Leitherer et al. (1999). The main goal is to constrain the age differences between different regions of a starburst. However, the achievable time resolution is limi-
ited by the age-extinction degeneracy. Without any data on extinction, the time resolution is limited to 5 Myr. This time resolution is not satisfactory for our purpose. We need to go down to time resolutions of the order of at least the free fall time to have a precise estimate of the time between two star forming events.

4.2) MosArgus

The main advantage of using integral field spectroscopy is the ability of the apparatus to give a spectra that ranges from ~ 3500 to 7000 Å on approximately 500 points all over the studied object. Such spatial extent of spectroscopic data allows more precise analysis than single slit spectroscopy where only some bright points on the galaxy’s surface are observed and spatial analysis is very limited. This is especially useful for extinction measurements since this quantity is rarely uniform all over a galaxy.

The use of MosArgus is twofold. First, it is useful for determining the physical properties of starburst galaxies. The oxygen abundance of the ISM can be probed with oxygen and nitrogen lines ([OII] 3727, [OIII] 4959, 5007 and [NII] 6548, 6583) while the electronic temperature can be determined if [O III] 4363 is detected. Second, MosArgus is a complementary tool to the BHK diagram. As outlined in the previous section, the time resolution of the BHK diagram alone is around 5 Myr and is mainly limited by the age-extinction degeneracy. Integral field spectroscopy allows Balmer extinction corrections for every point on the studied galaxy. This correction improves the achievable time resolution to 2 Myr and even lower, depending on the age of the regions studied (see Devost 1999 for details). A time resolution of that order is within the limits imposed by the free fall time which is about 2 Myr.

Conclusion

MosArgus and the BHK Diagram are two complementary tools that are needed for a better understanding of the star forming process in galaxies. Used together, they allow a reliable estimate of the time between the formation of different SSC in starburst galaxies. However, this knowledge of the chronology of events inside a star forming region is incomplete without the knowledge of the physical properties of the ISM that surrounds these star forming regions. It is essential to know the timescales of the star formation as well as the properties of the ISM where this star formation occurs to have a better understanding of the feedback process that takes place when stars form inside galaxies.

References

Devost, D. 1999, AJ Accepted
Seiden, P. E. & Gerola, H. 1982, Fund. of Cosmic Physics 7, 241

MOS-FP observation of NGC 5585 high resolution velocity field and rotation curve

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Figure 2: SSC age distribution in Arp 299. The age map (grey-scale) is shown superposed to the contours of the B image. In this picture, region A, B1 and C are the youngest (< 4 Myr) while region B2 is the oldest (7-10 Myr). North is up and east is left. The extent of the whole image is ~ 12 kpc at the assumed distance of 42 Mpc. The time resolution is limited by the data on extinction derived from the data of Mazzarelle & Boroson (1993).
Introduction

It has often been argued that since HI extends well outside the optical radius of spiral galaxies, it is best suited to probe their total mass and thus their dark matter content. With the aid of high resolution Fabry-Perot observations and high sensitivity Westerbrock HI data of NGC 5585, we show that mass model parameters are very sensitive not only to the flat part of the rotation curve (RC) but also to the rising part which can be derived with greater precision using 2-D Hα spectroscopy (Amram 1992). The large beam sizes of radio observations tend to lower the first few points of rotation curves and a posteriori corrections for that beam smearing effect are quite difficult (Begeman 1989, Swaters 1999).

What is now regarded as the classical method to study the mass distribution (van Albada et al. 1985, Carignan & Freeman 1985) is illustrated in Fig. 9 of Côté, Carignan, & Sancisi (1991) which shows the mass distribution of NGC 5585 using only its H I RC. Since this method is well explained elsewhere (see e.g. Blais-Ouellette et al. 1999), emphasis will be put here on the less well known Fabry-Perot data reduction itself. Results and conclusions will follow.

Fabry-Perot observations

The FP observations of the Hα emission line were obtained in February 1994 at the CFHT. The FP etalon (CFHT#1) was installed in MOS. A narrow-band filter (λ = 10 Å), centered at λ0 = 6570 Å (nearly at the systemic velocity of NGC 5585, Vsys = 305 km/s) was used. The field of view with no vignetting was 8.7' x 8.7', with 0.34" pix-1. The free spectral range (FSR) of 5.66 Å (258 km/s) was scanned in 27 (+1 overlapping) channels, giving a sampling of 0.2 Å (9.2 km/s) per channel. Eight minute integration was spent at each channel position.

Following normal de-biasing and flat-fielding with standard IRAF procedures, a robust 3-D cosmic-ray removal routine, that tracks cosmic rays by spatial (pixel-to-pixel) and spectral (frame-to-frame) analysis, is applied.

Because FP systems have multiple optical surfaces, some defocussed ghost reflections can be present (Bland-Hawthorn 1995), especially since the etalon couldn't be tilted at the time of observations (the etalon can now be tilted to send much of the reflection ghosts outside the field). In order to remove those reflections, we numerically simulate a reflection of each pixel of the images. We first build a convolution kernel that reproduces the reflection of a bright star in the field (Fig. 1). The reflection is composed of a bright peak and a defocused ring. We then simply convolve all the interferograms with the kernel and subtract the new images from the originals.

This procedure removes very efficiently all the reflected continuum and adequately but not perfectly (~80%) the monochromatic emission. The main problem arises when one tries to remove the defocused rings around all the reflections (side peaks in Figure 1b). With FP spectroscopy, the transmitted intensity of a specific wavelength depends on the exact distance from the FP center. That is why the slight variation in position along the reflected annulus produces a significant variation in intensity for any monochromatic signal. These variations are in practice very difficult to reproduce and these annuli were minimally subtracted to avoid "holes" in the images.

The presence of strong night sky lines combined with photometric variations (transparency, seeing) from one exposure to another are the two major sources of noise in our spectra. Since these spectra are acquired sequentially it is of prime importance to minimise any background variation from one channel to the other. This background includes continuous, diffuse light and monochromatic emission from atmospheric OH radicals and from geocoronal Hα, that both vary spatially and temporally. The interference pattern of the sky emission lines (circles in Fig. 2) makes impossible the normal evaluation of the background in pure sky regions. To overcome this difficulty, we use the radial symmetry of the FP : the sky is evaluated by azimuthally summing rings of con-
stant phase after masking the galaxy signal. The computed background is then removed in each ring.

Once the background is subtracted, it is theoretically possible to use the stars in the field to normalize the photometry but the operation would add significant noise to the spectra. Since the photometric variations were rather smooth during the night, no transparency correction is applied. Ideally the flux of the guiding star, that is not affected the same way by the telluric lines, would be used for the photometric corrections but it is not yet available at the CFHT.

Once the interferograms are assembled in a cube, a neon calibration lamp (6598.95 Å) is used to fix the zero point of each spectrum. To be totally device independent, the theoretical position of a sky emission line is then used to fine-tune the phase (wavelength origin) at each pixel in order to get a particular wavelength on an exact x - y plane. Due to the limited free spectral range, this telluric line is a composite of geocoronal Hα (6562.74 Å or 517 km/s) and of an OH line (6568.78 Å or 532 km/s). Since there is no way to determine the relative contribution of each line, we are left with some uncertainties on the systemic velocity of the galaxy, but this does not affect the relative velocities and the RC. In order to get a particular wavelength on an exact x - y plane, Due to the limited free spectral range, this telluric line is a composite of geocoronal Hα (6562.74 Å or 517 km/s) and of an OH line (6568.78 Å or 532 km/s). Since there is no way to determine the relative contribution of each line, we are left with some uncertainties on the systemic velocity of the galaxy, but this does not affect the relative velocities and the RC. In order to get a particular wavelength on an exact x - y plane, Due to the limited free spectral range, this telluric line is a composite of geocoronal Hα (6562.74 Å or 517 km/s) and of an OH line (6568.78 Å or 532 km/s). Since there is no way to determine the relative contribution of each line, we are left with some uncertainties on the systemic velocity of the galaxy, but this does not affect the relative velocities and the RC. In order to get a particular wavelength on an exact x - y plane, due to the H I parameters are not well defined, we decided to use for the final model the Hα data for r < 120" and the H I data for r > 120". This adopted model is showed in Fig.4. The parameters of the model are: (M/LB)* = 0.8, rc = 3.9 kpc and σ = 53.3 km/s. As expected, this σ is very similar to the one derived from the H I RC because this parameter is a measure of the maximum amplitude of the RC, which is mainly defined by the H I data in the outer parts. However, the two other parameters (M/LB)* for the stellar disk and rc of the dark halo (which are coupled) have nearly the same values as those derived from the Hα curve alone. This is because (M/ LB)* of the luminous stellar disk, and hence the scaling parameter of the dark halo rc , is mainly constrained by the H II data in the inner parts.

Conclusions

The importance of an accurate determination of the rising part of a rotation curve using full 2-D high resolution FP observations is well illustrated by the example of NGC 5585. The principal conclusions are :

1. The parameters of the mass distribution of both the dark and the luminous components are very sensitive to the rising part of the RC (the first few velocity points) not only in early-type spirals, where the velocity gradient is large in the inner parts, but also in late-type spirals, which have a much shallower gradient. The sensitivity is especially important when the contributions of dark and luminous matter are comparable.

2. Full 2-D spectroscopy, obtained with Fabry-Perot spectroscopy, is to be preferred to long-slit spectroscopy in order to derive properly the
orientation parameters (namely, the rotation center and the position angle) and hence not underestimate the rotational velocities.

3. Combining new Hα CFHT FP data with Westerbork HI data reduces the ratio $M_{\text{dark}}/M_{\text{lum}}$ by ~30% via an increase in the core radius by 30% for the late-type spiral NGC 5585. If such large errors are common, one could imagine that it could mask any physical correlation between the parameters of the dark and the luminous matter.

4. Finally, the optimal RC for a spiral or a dwarf galaxy is clearly a combination of 2-D high resolution spectroscopy for the inner part and high sensitivity radio observations for the outer regions.

The results of this investigation provide one of the main motivations behind the GHASP (Gassendi survey of HAlpha in SPiral galaxies) project, which intends to map accurately the Hα velocity fields of ~200-300 nearby spiral and dwarf galaxies using FP observations. This is the project of a consortium composed of the Institut Gassendi (Observatoire de Marseille, Laboratoire d’astronomie spatiale in Marseille and the Observatoire de Haute Provence), the Observatoire du mont Megantic, the Observatoire de Paris-Meudon and the Kapteyn Institute. The candidate galaxies will be selected from the WHISP (Westerbork survey of HI in Spiral Galaxies) project, which intends to map the HI in ~1000-3000 galaxies in the next ten years. This should provide an ideal sample to study possible correlations between the parameters of the DM halos and other properties of the galaxies.

References


Begeman, K.G. 1987, PhD thesis, Rijksuniversiteit, Groningen
Bland-Hawthorn, J., ASP conf series, 71, 81
Côté, S. 1995, PhD thesis, Australian National University, Canberra

A wide-field spectroscopic survey of the cluster of galaxies C10024+1654

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In standard hierarchical models for structure formation in the Universe, clusters of galaxies are the most recently formed gravitationally bound entities. Therefore, the evolution with redshift of the mass function of clusters gives important constraints for cosmological models, in particular for the amplitude of the fluctuation power spectrum $\sigma_8$ and the matter density $\Omega$ (see e. g. Eke et al. 1996).

Cluster masses can be estimated in a variety of ways, (i) from the luminosity or temperature of the hot, X-ray emitting, intergalactic medium, (ii) from the weak and strong gravitational lensing effects on background galaxies, or (iii) from the kinematics of the cluster galaxies by applying the virial theorem. Each of these methods depends on a certain set of assumptions, in particular concerning the detailed structure of the cluster. Before applying these methods statistically to cluster populations at different redshifts, it is therefore necessary to study individual clusters in detail. Spectroscopic surveys in a wide field around the cluster yielding large numbers of redshifts for cluster members as well as foreground and background galaxies give important information about the detailed spatial and kinematic structure in the cluster. One also gains important information about possible structure in the

Figure 4: (see text)
distribution of foreground and background galaxies, useful for interpreting lensing or X-ray data.

Cl0024+1654 (z=0.39) is one of the best studied clusters of galaxies at intermediate redshift. Figure 1 shows a subsection from an I band image of the cluster obtained with the UH8k camera on CFHT. The image shows the inner part of the cluster and the giant arcs are clearly visible. Cl0024 was one of the original Butcher-Oemler clusters where a higher fraction of blue galaxies as compared to low redshift clusters was observed (Butcher & Oemler 1978). Whereas in many relaxed rich clusters the masses derived by different methods agree reasonably well, mass determinations for Cl0024 have led to strong discrepancies, with the dynamical and lensing estimates being higher than the X-ray estimate by a factor of 2 or more (Soucail 1998). However, the dynamical estimate was based on 33 redshifts only (Schneider, Dressler & Gunn 1986) making it desirable to obtain a larger number of redshifts.

Here we report on a wide-field spectroscopic survey of this cluster, covering a field up to about 1.2 h$^{-1}$ Mpc at the cluster redshift. Figure 2 shows a mosaic of 9 V-band exposures obtained with EMMI at the ESO NTT. Overlaid on this are the positions of all the objects for which spectra have been obtained.

Spectra were obtained with the CFHT MOS in August 1993 (44 targeted objects), 24-28 August 1995 (237 objects) and 11-12 November 1996 (82 objects). An additional 389 spectra were obtained on 12-16 September 1996 using the LDSS-2 multi-slit spectrograph on the 4.2m William Herschel Telescope (WHT). The spectra were reduced using the multired package by Olivier Le Fèvre based on standard IRAF tasks.

Figures 3 shows an example of a typical spectrum (observed with CFHT-MOS) as well an image of the object cut from our UH8k I-band image. As yet, redshifts have only been identified by visual inspection. For the CFHT data (only 1995 run) we thus obtain 132 redshifts which we consider “probable” or “secure”. The total number of targeted objects is 237, giving a (preliminary) success rate of 56%. Among the 389 WHT spectra we find 247 probable or secure redshifts, i.e. a success rate of 63%. These are good results for such a distant cluster. We hope to further improve on these numbers to a success rate of around 75% by cross-correlating our spectra with template spectra.

Histograms of our “probable” or “secure” redshifts are shown in Figures 4 and 5. The cluster clearly shows up in Figure 4, whereas no obvious structure is seen in the distribution of foreground and background objects. The zoom on the cluster redshift in Figure 5 clearly shows a
bimodal distribution of redshifts. The main peak is at a central redshift of 0.3949 and has a velocity dispersion of (725 $\pm$ 75) km/s. The smaller peak at central redshift of 0.383 has a (formal) velocity dispersion of (670 $\pm$ 170) km/s. The two dimensional distribution of the galaxies in this foreground peak coincides roughly with the distribution of the galaxies in the main peak. Given the difference of $\Delta z = 0.012$, corresponding to a separation of about 2.6 Mpc/$h$ at the cluster redshift or a velocity difference of 2600 km/s, we consider it unlikely that this peak forms a part of the galaxy cluster. Therefore it seems that we can resolve the discrepancy between the different mass estimates for Cl0024: Using a velocity dispersion of $\sigma = 725$ km/s and preliminarily modelling the mass distribution as a simple isothermal sphere, we estimate $M = 7.3 \times 10^{14} M_{\odot}$ at $R<1$ Mpc which is roughly consistent with the mass determined from ROSAT/HRI data: $M_X = 3 \times 10^{14} M_{\odot}$ for $R<0.5$ Mpc. Note that these results are preliminary - clearly Cl0024 is not a relaxed cluster, so more detailed modelling will be required to accurately determine its dynamical mass.

The reason for the discrepancy noted before seems to be that given the small number of cluster galaxy redshifts known so far, the bimodality of the redshift histogram wasn’t seen at high significance. Therefore both peaks were considered as belonging to the cluster proper leading to an artificially high estimate for the velocity dispersion and for the mass. Also, having a second mass concentration in the line of sight of the cluster enhances the gravitational lens effect, again leading to a high mass estimate. By contrast, the X-ray emission is only due to the main peak (the surface brightness scales as the square of the gas density) with no or very little contribution from the foreground peak.

The current observations show how a dedicated observing effort can help in understanding and solving cosmological problems. In the near future, similar spectroscopic surveys will be easily done on the new generation of 8m telescopes and instruments. Thanks to the CFHT and WHT capabilities, such a survey was made possible today, paving the way for future surveys on upcoming facilities.

References

Butcher, H., Oemler, A. 1978, Astroph. J. 219, 18
Schneider, D. P., Dressler, A., Gunn, J. E. 1986, Astron. J. 92, 523

La transformation des galaxies spirales

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Étant donné qu’elles sont le produit de la formation et de l’évolution stellaire, les abondances chimiques sont un outil puissant pour l’étude de l’évolution des galaxies. Par exemple, la pente et la forme du gradient d’abondance dans le gaz interstellaire sont reliées à des propriétés globales des galaxies spirales qui évoluent avec le temps: ce sont par exemple la présence de barre, la densité de surface et la masse totale ou la magnitude absolue (Dutil & Roy 1999, et références). Une relation possible entre l’amplitude du gradient et le type morphologique a aussi été suggérée (Pagel 1991; Oey & Kennicutt 1993; Zaritsky, Kennicutt & Huchra 1994). Toutefois, malgré les efforts déployés pour mesurer la teneur en éléments lourds, la majorité des observations ont portées sur des galaxies de type tardif: la mesure des raies nébulaires, qui y sont plus brillantes, est facilitée par des niveaux d’abondance faibles ou modérés.

Néanmoins, les quelques travaux sur les galaxies spirales de type précoce ont donné des résultats utiles (Oey & Kennicutt 1993, Zaritsky, Kennicutt & Huchra 1994). Comparées aux galaxies de type tardif non-barrées (Sbc, Sc et Sd), les galaxies de type précoce présentent une abondance O/H plus élevée et un gradient plus plat. Cette tendance peut d’une part être expliquée par l’action d’une barre transformant le type morphologique en un type plus précoce et qui, du même coup,
aplatit le gradient d’abondance en induisant un mélange de gaz à travers le disque (Pfenniger 1992; Friedli & Benz & Kenicutt 1994, Friedli & Benz 1995). Alternativement, l’aplatissement du gradient d’abondance peut être interprété comme résultant d’un épisode de vieillissement du gaz interstellaire et d’une saturation de la production des métaux à mesure que le gaz est emprisonné dans les étoiles (Mollá, Ferrini & Díaz 1997); dans ce modèle, cet effet de vieillissement n’implique pas de variation du type morphologique. Ces tentatives d’explication ne sont malheureusement basées que sur un petit nombre de galaxies pourvues d’un aplatissement d’abondance (moins de 10 régions HII).

Pour combler cette lacune, le multiplexage est crucial. A l’aide des méthodes d’imagerie spectro-photométrique et de spectroscopie multifente, nous avons dérivé les gradients d’abondance O/H dans huit galaxies spirales de type précoce à partir de 549 régions HII. Dans le cadre de ce programme, cinq galaxies (NGC 1068, NGC 2841, NGC 3368, NGC 4258 et NGC 7331) ont été observées à l’Observatoire du Mont Mégantic (OMM) à l’aide de l’imagerie spectrophotométrique obtenue avec le réducteur local Panoramix (La réincarnation du réducteur focal Palila du TCFH). Les galaxies NGC 2460 et NGC 3351 et NGC 4501 ont quant à elles été observées au TCFH avec le spectrographe multifente MOS (voir Fig 1). Les temps d’intégration typiques étaient de 55 000 sec par galaxie à l’OMM et de 8000 sec par masque avec MOS (au moins trois masques sont nécessaires pour bien échantillonner une galaxie).

Pour donner une portée plus globale à nos observations, nous avons examiné le comportement de l’abondance extrapolaé au centre en fonction du type morphologique (Fig 2). Deux séquences distinctes apparaissent clairement: les galaxies fortement barrées (ε_b > 4) et les galaxies faiblement barrées (ε_b</= 4). Les galaxies fortement barrées montrent une abondance centrale inférieure d’environ 0.5 dex par rapport aux galaxies non-barrées. Toutefois, cette séparation en deux groupes disparait chez les galaxies de type précoce. En effet, les galaxies de type précoce (T </= 3) s’alignent sur la séquence des galaxies barrées (on fait exception des objets considéré en phase de transformation). Nous interprétons ce changement de comportement chez les galaxies de type précoce comme étant dû à l’action passée d’une barre, maintenant plus faible ou disparue. Un tel scénario est prédit par les modèles de Friedli & Benz (1993, 1995). La dissolution de la barre est associée à la croissance du bulbe et possiblement à une transformation morphologique (Combes et al. 1990; Norman, Sellwood & Hasan 1996), puisque qu’en se dissolvant une barre est capable de produire un bulbe aussi gros qu’elle (Pfenniger 1998). Cette hypothèse explique aussi pourquoi les gradients sont plats chez les galaxies de type précoce quelque soit la force de la barre; en effet, suivant cette hypothèse, toutes ces galaxies ont été fortement barrées à un moment ou autre de leur histoire, subissant du même coup un aplatissement important de leur gradient d’abondance qui n’a pu revenir à sa valeur originale par la suite.

Quelques objets apparaissent comme étant en pleine phase de transformation. Cet état se traduit par la présence d’une cassure dans le gradient d’abondance, signe distinctif d’une barre jeune (quelques centaines de millions d’années; Friedli, Benz & Kenicutt 1994). Ce phénomène est observé pour NGC 3359 et NGC 1365 (Martin & Roy 1995; Roy & Walsh 1997) et probablement aussi dans le cas de NGC 3319 (Zaritsky, Kenicutt & Huchra 1994). Les résultats des simulations numériques permettent d’estimer l’âge de ces barres entre 500 millions et un mil-

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l'abondance centrale dans un espace multi-dimensionnel. Ces dimensions sont le type morphologique. Comme dans le cas du diagramme H-R l'évolution a lieu et les vides comme des zones de transition rapide ou d'impossibilité d'objets comme des zones de stabilité relative où l'évolution est lente, l'applatissement du gradient dû aux effect de saturation de la production des métaux chez les galaxies non-barrées est aussi un de ces mécanismes (Ferrini et al. 1994). Toutefois, contrairement au diagramme H-R, le lien entre les observations et les modèles n'est pas encore clair. Par exemple, les modèles multiphases de Ferrini et al. (1994) indiquent des variations de la pente du gradient, mais ils sont muets sur les variations de type morphologique (Mollá et al. 1996, 1997).

À la lumière de ces résultats, nous proposons une analogie avec le diagramme Hertzprung-Russell. Nous interprétons les concentrations sur les galaxies non barrées, la droite inférieure sur les galaxies barrées. Les carrés représentent des galaxies avec des barres fortes ($e_b > 4$); les cercles des galaxies avec des barres faibles. Les symboles pleins indiquent les données sur les galaxies de type précoce provenant notre étude, les symboles vides proviennent d'autres travaux. Les X indiquent que les galaxies sont dans une phase de transformation. La droite supérieure représente l'ajustement sur les galaxies non barrées, la droite inférieure sur les galaxies barrées.

Figure 2: Abondance centrale O/H projetée en fonction du type morphologique. Les carrés représentent des galaxies avec des barres fortes ($e_b > 4$); les cercles des galaxies avec des barres faibles. Les symboles pleins indiquent les données sur les galaxies de type précoce provenant notre étude, les symboles vides proviennent d'autres travaux. Les X indiquent que les galaxies sont dans une phase de transformation. La droite supérieure représente l'ajustement sur les galaxies non barrées, la droite inférieure sur les galaxies barrées.
CFHT High Resolution Fourier Transform Spectroscopy of H$_2$ IR emission in NGC 7023

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Abstract

The purpose of the work reported here is to study the temperature and dynamics of gas surrounding a newly-formed massive star. Bright IR emission from molecular hydrogen is characteristic of the inner edges of such environments and provides a means of observing mass motions and the kinetic temperature of the medium.

NGC 7023, a reflection nebula, represents an early phase of stellar evolution. A young star HD200775, of spectral class B2.5Ve, illuminates and interacts strongly with the remnant of its dense parent molecular cloud, 0.1 pc distant from the star, exposing it to a radiation field $\sim 10^4$ times that of the average interstellar UV field. This photodissociation or “photon-dominated” region (PDR) has been extensively studied and there are numerous other data, especially in the radio (e.g. Fuente et al., 1998, Gerin et al., 1998) to combine with our IR data. IR images of H$_2$ emission of NGC 7023 have also been reported (Lemaire et al., 1996).

We investigate the dynamics and temperature of the H$_2$ emitting zone, through determination for the first time of the H$_2$ IR emission linewidth and velocity. A determination of linewidth, translated into temperature, places useful constraints on PDR models. A grey-scale plot of the H$_2$ emission (Lemaire et al., 1996) is shown in Fig. 1 with a circle to mark the position and extent of the region observed in the current work.

Our observations of the strong S(1) v=1-0 H$_2$ line were performed using the CFHT equipped with the Fourier Transform Spectrometer (FTS: Maillard and Michel 1982). Observing for 4 hours, a spectral resolution of $\sim 125,000$ was achieved, that is $\sim 2.4$ km s$^{-1}$. Fig. 2 shows the S(1) line over a range of 0.27 cm$^{-1}$. The line centre is blue-shifted by 0.28 cm$^{-1}$ at 4713.1863 cm$^{-1}$ and the full width at half maximum (FWHM) of the line is 3.4 km s$^{-1}$.

The measured line centre is blue-shifted by 0.2809 cm$^{-1}$ from the rest-framed frequency. Following corrections, the corresponding $v_{lsr}$ for our observed H$_2$ line is $+3.75 \pm 0.25$ km s$^{-1}$. A comparison with radio-data (Gerin et al., 1998, Fuente et al., 1998, Fuente et al., 1996) is given in Table 1, showing that there is a gradient of velocity from the atomic gas into the molecular gas. The velocity data in Table 1 provide the first clear observational evidence of gas of a parent molecular cloud not at rest with respect to a dissociation front.

H$_2$ is at a kinetic temperature of 500 $\pm$ 70K, purely on the basis of the measured linewidth. For comparison, ISO SWS data of Moutou et al. (1998) show a kinetic temperature for this region of $\sim 400$K, derived from a Boltzmann plot involving H$_2$ rotational lines.

Detailed consideration of the linewidths in Table 1 shows that data support the general picture of PDRs developed from detailed modeling. Some turbulent broadening of $\sim 0.8$ km s$^{-1}$ is required for consistency, for example in the CI emission line.

Our observational data require that the HI zone should be at 750K, the H$_2$ zone at 450K and the CI zone at 100K. Additional constraints are the observed emissivity (Lemaire et al., 1996) and the observed S(1)/S(2) v=1-0 line ratio = 2.7 $\pm$ 0.3 (Lemaire et al., 1996; Martini et al., 1997). Attempts to fit these data, for example using a code based on that in Abgrall et al. (1992), met with only limited success, noting that this model includes computation of the thermal balance and thus of the kinetic temperature of the H$_2$ emitting zone. Values of number density or of pressure (or temperature x density) deduced are how-

Figure 1: Experimental data (black squares) showing the H$_2$ v=1-0 S(1) line over a range of 0.27 cm$^{-1}$. The dotted line is the lineshape function associated with the interferometer. The solid line is a fit to the observations obtained by convoluting the instrumental lineshape function with a gaussian.

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ever in good agreement with values reported elsewhere e.g. Martini et al., (1997).

The successes and failures of current models apart, our demonstration of relative flow requires a consideration of time-dependent effects within the PDR in NGC 7023. Advection of warm material (Hollenbach and Tielens 1999) from the outer part of the PDR into the cooler part, say, would increase the temperature deeper into the PDR over the value estimated purely from the atomic and molecular microphysics. The advection of irradiated material in the PDR has not been considered in models of a pure PDR.

In conclusion, it is evident that NGC 7023 is a dynamically interesting region. Both low and high resolution (R~25,000) data, obtained using the BEAR instrument on the CFHT, are presently being analyzed and promise to shed further light on the dynamics of NGC 7023 and introduce further constraints on PDR models.

References


Table 1: Velocities in $v_{lsr}$ and widths for HI data (Fuente et al, 1996), H$_2$ (present work), CII, CI and CO (6-5, 3-2) emission data (Gerin et al, 1998) and $^{13}$CO (1-0) emission data (Fuente et al, 1998. Linewidths in the second column are values at full-width-half-maximum.

<table>
<thead>
<tr>
<th>Species observed</th>
<th>Linewidth (/km s$^{-1}$)</th>
<th>Velocity (/km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI</td>
<td>6</td>
<td>4 to 5</td>
</tr>
<tr>
<td>H$_2$</td>
<td>3.4</td>
<td>3.75 +/- ~0.25</td>
</tr>
<tr>
<td>CII</td>
<td>3.4</td>
<td>2.8 +/- ~0.1</td>
</tr>
<tr>
<td>CI</td>
<td>1.2</td>
<td>2.25 +/- ~0.3</td>
</tr>
<tr>
<td>$^{13}$CO(6-5)</td>
<td>1.5</td>
<td>2.6 +/- ~0.3</td>
</tr>
<tr>
<td>$^{13}$CO(3-2)</td>
<td>0.6</td>
<td>2.5 +/- ~0.3</td>
</tr>
<tr>
<td>$^{13}$CO(1-0)</td>
<td>---</td>
<td>1.9 +/- ~0.5</td>
</tr>
</tbody>
</table>

In the Semester 1994I issue of the CFHT Information Bulletin, Pierre Couturier very boldly listed seven priorities for the duration of his term as Executive Director. My scorecard reads 5.5/7.0, with some progress in all areas. This is a remarkable record and leaves a solid foundation for the future. Many elements of the program initiated by Pierre will be continued. In particular, the search for increased operational efficiencies and improvements in the reliability of the Observatory instruments and telescope subsystems. The quality of support services offered to observers will continue to be enhanced both on and off the