GBT Memo # 277

A radio multiobject spectrograph

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Abstract.
We discuss the scientific need and requirements for a radio multiobject spectrograph. This would be a focal plane array with individually adjustable 'slit' positions to perform spectroscopy on ∼10's of objects in the focal plane of the GBT simultaneously. The slit positions would be defined via previous surveys at submm or other wavelengths. Such multiobject spectrographs have been essential to the advance of optical astronomy in the past 10 years. Such a multiobject spectrograph could keep the GBT competitive for line stiudies of high z galaxy even during the era of ALMA.

1. Introduction

Multiobject spectrographs have revolutionized optical astronomy by enabling wide area studies of galaxy formation by obtaining many (10's to 100's) optical spectra simultaneously through a slit-mask with pre-defined positions (eg. the 2DF, DEEP, and VIMOS surveys; eg. LeFevre et al. 2003, SPIE 4841, 1670). These pre-defined positions are set through broad or narrow band optical imaging, or as targets selected through surveys at other wavelengths (submm, Xray, or radio).

Centimeter and millimeter observatories are slowly increasing the use of the focal plane of their telescopes. These programs have focused on 'integral field' units, ie. devices that densely cover a given area.[1] Bolometer cameras have made major contributions in imaging the broad band continuum emission over wide fields (10's arcmin) to mJy levels at (sub)mm wavelengths. MMIC-based focal plane arrays for integral field spectroscopy have also been built[2], consisting of 16 independent beams, again, densely covering the central part of the focal plane. Lastly, interferometers inherently cover larger areas due to the larger primary beam of the smaller antenna element, and plans are being made to increase this area through focal plane arrays on interferometers. However, for the present, interferometers have fairly limited FoVs above 10 GHz or so, eg. ALMA has a FoV = $23''$ FWHM at 230 GHz.

There are many physical problems that do not require dense areal coverage of the focal plane, but are best done using individual 'slits' with adjustable positions, to take spectra of pre-defined objects in the field, as has been done in the optical with multiobject spectrographs. In this memo we outline a number

[1] Dense coverage in this case means single mode horns packed as closely as allowed by the geometry of the system, which typically corresponds to beam separations of two times the primary beam FWHM.

[2] http://www.astro.umass.edu/~fcrao/instrumentation/sequoia/seq.html

of possible science cases for a radio multiobject spectrograph. This list is not meant to be exhaustive, but only illustrative of the kind of science that can be done with a radio multiobject spectrograph. We then consider some of the design specifications, and potential implementation at the GBT.

2. Science cases for a multiobjectgraph

As a baseline system, we assume a multiobject spectrograph covering the Ka band. This corresponds to CO 1-0 at $z = 1.8$ to 2.8, and CO 2-1 at $z = 4.7$ to 6.7. It also includes dense gas tracers such as HCN 1-0 at $z = 1.2$ to 2.0, and HCN 2-1 at $z = 3.4$ to 4.9. The idea of a multiobject spectrograph is relatively generic, and could be applied from 20 GHz to 90 GHz, or beyond.

2.1. (sub)mm deep fields

Bolometer cameras have led to amazing advances in the study of galaxy formation, by revealing a population of optically obscured, active star forming galaxies that may dominate the cosmic star formation rate density at $z \sim 2$, possibly representing the formation of large elliptical galaxies (Blain, A. et al. 2002, Phys.Rev. 369, 111). Dust masses of order 10^8 have been detected in galaxies out to $z = 6.4$ (Bertoldi, F. et al. 2003a, A& A, 406, L55), indicating that dust and molecular gas enrichment occur very early in the history of galaxy formation. A major follow-up study of these systems is to detect and image the molecular gas – the requisite fuel for star formation in galaxies. Through pain-staking observations of individual objects, a total of 40 high z 'molecular emission line' galaxies (EMGs) have been identified (Solomon & van den Bout 2005, ARAA, 43, 677).

A typical (sub)mm deep field covers $10'$ to $30'$, and detects about 20 objects down to 4mJy or so at 250 GHz. The galaxies are typically in the range of $z \sim 1.5$ to 3. A major campaign was made with the PdBI to search for CO emission from a subsample of these submm galaxies, and a number of new EMGs were detected through this dedicated campaign, one object at a time, occupying a significant fraction of the PdBI observing time in 2004 (Greve et al. 2005, MNRAS, 359, 1165). Extrapolating from the higher order transitions, the implied typical CO 1-0 lines will have peaks of $\sim$ 1mJy, and line widths between 300 and 1000 km s^{-1}. The gas masses are of order 10^{10} M$_\odot$. We note that, in some systems the gas could be subthermally excited (Hainline et al. 2006 ApJ, in press; Papadapoulos et al. 2005, A&A, 444, 813), in which case the lower order CO lines could be signficantly stronger than predicted assuming constant brightness temperature.

For the submm galaxies, optical redshifts are often difficult to obtain. Photometric redshifts are uncertain, depending on the assumed template, but photometric redshifts typically can be narrowed down to $\Delta z \sim 0.2$, or $\Delta\nu \sim$ 2GHz for the Ka band (Bertoldi et al. 2006, ApJ COSMOS special issue, in press).

2.2. Dense gas tracers

Gao & Solomon (ApJS, 152, 63, 2005) have shown that lines such as HCO+ and HCN are good tracers of the dense molecular clouds ($\geq 10^4$ cm^{-3}) directly associated with star formation in galaxies.

For the submm galaxies, the CO line luminosities are such that one could also perform a search for these dense gas tracers. These lines are typically fainter than CO by a factor of a few to 10 (Carilli et al. 2005, ApJ, 618, 586). A multiobject spectrograph allows for a stacking analysis to be done, thereby increasing the sensitivity to the mean dense gas properties of the population by a factor 5 or so (ie. square root of number of objects observed simultaneously). Looking at multiple sources in cluster lensing systems can also push down to an order of magnitude lower mass systems.

2.3. Lyman Break Galaxies

The Lyman break galaxies (LBGs) are the most populous galaxy population yet identified at intermediate to high redshift ($z \sim 2$ to 5; Giavalisco 2002, ARAA 40, 579). These galaxies are considered to be the 'normal' galaxy population at these redshifts. The star formation rates derived from UV luminosities are typically an order of magnitude smaller than for submm galaxies (ie, 10 to 100 $M_\odot$ year^{-1} for LBGs, as opposed to 100's to 1000's for submm galaxies), although this is modulo an uncertain dust extinction correction for the LBGs.

Current telescopes lack the sensitivity to detect molecular line emission from individual LBGs. However, a stacking analysis of Lyman break galaxies increases substantially the sensitivity, at least to the mean properties of the sample, and would be the only means of determining meaningful constraints on the molecular gas properties of 'normal' galaxies during the epoch of most active galaxy formation ($z \sim 2$ to 4), prior to the next generation telescopes, such as ALMA (Greve & Sommer-Larsen, ApJL, in press). The LBGs also have a major advantage in that the redshifts are determined to within ~ 100 km s^{-1}, or 11 MHz at 35 GHz. Multiple simultaneous observations of a large number of LBGs could also identify the few galaxies that happen to be highly dust obscured, extreme starbursts.

2.4. Lyα emitting galaxies into reionization

Narrow band optical imaging in the redshifted Lyα line has pushed the field of galaxy formation to the edge of cosmic reionization ($z \sim 6$; Bunker et al. 2005, NewAR, 50, 94; Malhotra & Rhoads 2006, ApJ, 647, L95; Ajiki et al. 2006, ApJ, COSMOS special issue, in press). An important question in the study of high-z Lyα emitters (LAEs) is the molecular content of the galaxies. The implied star formation rates based on the Lyα line are typically low ($\sim$ few to 10's $M_\odot$ year^{-1}), but there is substantial uncertainty due to the obscuration correction, and there remains the potential for a subpopulation of very dusty, gas rich starburst galaxies. A radio multiobject spectrograph would be ideal to search for the molecular gas reservoirs in a large sample of LAEs through observation of the CO 2-1 line – a crucial aspect of any complete study of galaxy formation.

The optical surveys for LAEs typically yield about 25 galaxies per 0.5 square degrees for a narrow band filter centered at $z \sim 6$, and the redshifts are confirmed to high accuracy through follow-up multiobject spectroscopy. The CO 2-1 line will be weak for a typical object, so the thrust behind a CO study would be to search for the subsample of very dusty starbursts within the LAE sample with substantial molecular gas reservoirs ($\sim 10^{10}$ $M_\odot$). These systems would be the precursors of large elliptical galaxies. One could also perform a stacking analysis, and potentially get a limit to the mean molecular gas properties of the LAE population a factor 5 or so deeper than for individual objects.

2.5. Nearby star forming galaxies

Star formation in nearby galaxies often occurs in dense, optically obscured, 'giant HII regions' or 'super star clusters'. A multiobject spectrograph can be used to target multiple superstar clusters, or other objects in the nuclei, or spiral arms, of nearby galaxies. An excellent example is the recent study of the giant HII regions in the spiral arms of M101 (Chen et al. 2005, ApJ 619, 770). A multiobject spectrograph at K or Ka band could study lines from ammonia, water, methanol, C_3H_2 (the ring molecule), SO, and many others.

3. Design specifications and implementation

We review some of the design specifications of such a radio multiobject spectrograph.

- **Field-of-View:** The required area over which 'slits' need to be set is typically $10'$ to $30'$, comparable to the standard deep submm fields, or LBG fields, or LAE searches. For the GBT, Norrod & Srikanth (GBT memo 198) have done a numerical investigation of the FoV at 46 GHz. They find that the focal plane is easily adequate to facilitate this area: a throw of 50cm off-axis corresponds to $9'$ at 46 GHz, and the beam efficiency is still 60%. The limitation may be fitting the system inside one of the feed mounting rings of the receiver turret, which have radii = 30cm or 45cm.

- **Number of 'slits':** Current surveys for the different high z galaxy types typically find of order 25 objects in a given $\sim 20'$ field. Hence, between 16 and 25 slits would be adequate.

- **Reconfiguration and tracking:** The system will be required to integrate for a few hours on a given field, and hence the slits will need to counter-rotate with parallactic angle changes. Reconfiguration could be done on daily timescales.

- **Spectrometer and IF:** Redshifts for the LBGs and LAEs are well determined (100's km/s), and hence spectrometers with a bandwidth of ≤ 0.3 GHz per slit are required. However, the submm galaxies have more poorly determined redshifts, $\Delta z \sim 0.2$, or $\Delta\nu \sim 2$GHz for the Ka band. Hence, a spectrometer covering at least 1 GHz per slit is needed. One could potentially build a spectrometer where one could trade off number of objects with bandwidth, depending on the problem.

- **Beam switching:** The full array might be used for sky removal, in a manner similar to current arrays, although the angular scales may become an issue.

- **Integral field spectroscopy:** The system can also be close-packed, to perform integral field spectroscopy analogous to the standard heterodyne focal plane arrays currently in use.

We have discussed some potential implementation schemes at the GBT. The key specification is that the slits must be adjustable over the full focal plane (up to 50 cm throw). Following are some (rough) ideas:

- The simplest idea would be to have independent single mode horns/receivers that can be moved, but shared cryogenics may require that the receivers all be close-packed. An alternative may be individual, compact cryogenic units for each receiver, with a likely penalty in non-optimum receiver temperatures.
- If the amplifiers need to be close-packed, then one could consider moveable feeds with flexible waveguide. The noise performance may be significantly degraded in this case.
- Another possibility is to use adjustable mirrors. The difficulty here would be general optical layout and tracking.
- A brute-force solution would be to build a very large focal plane array, and simply choose feeds at the source positions. The problem here is that most single mode horn-based arrays are highly undersampled spatially, such that the probability of having beams at the positions of all, or even most, of the target sources in a given field is low. Over-sampled, 'phased arrays' have been considered, in which case one could synthesize beams at each target source position, but 2D versions of these arrays are still in the experimental state.

Clearly, we have not explored the technical issues in detail. However, the scientific impetus may be great enough to pursue possible engineering solutions to the radio multi-object spectrograph. A multiobject spectrograph at the GBT would keep the telescope competitive for line studies of distant galaxies even in the era of ALMA – ALMA can only look at one object at a time.

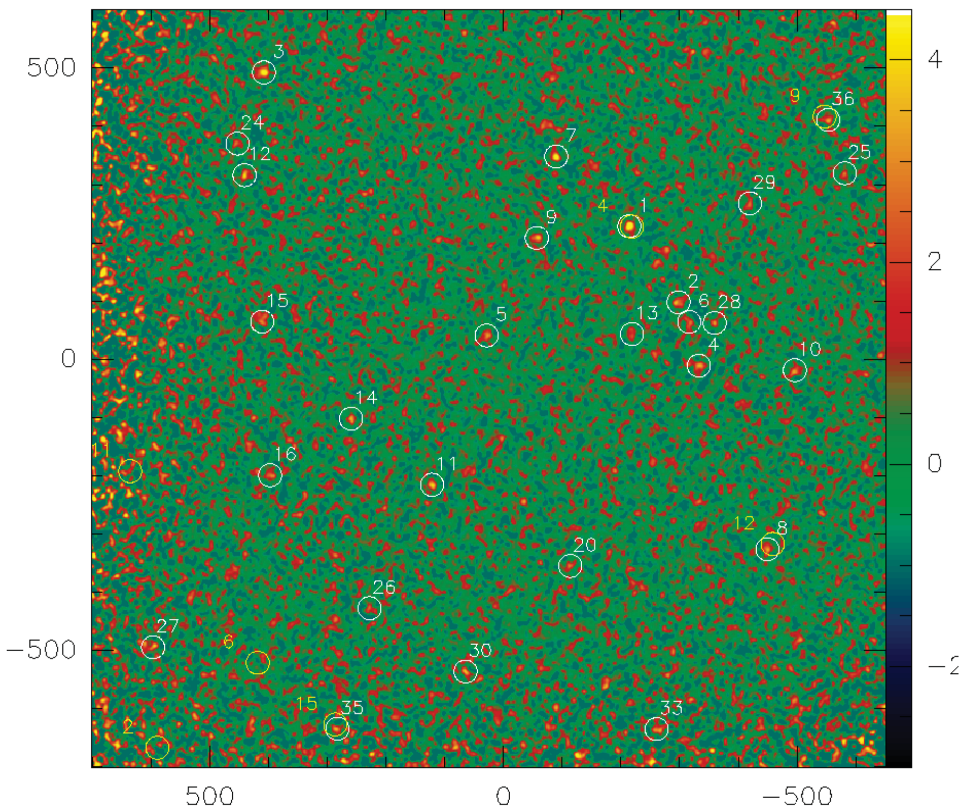

Figure 1. The MAMBO 250 GHz image of the COSMOS field (Bertoldi et al. ApJ Cosmos Special Issue, in press). About 15 secure submm sources are detected in a region of 20′ on a side.