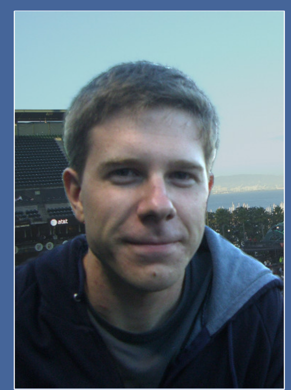
Exploring the FIR-Radio Correlation with Continuous Spectra from the ATA



Peter K. G. Williams
UC Berkeley
pwilliams@astro.berkeley.edu

Geoffrey C. Bower
UC Berkeley
gbower@astro.berkeley.edu

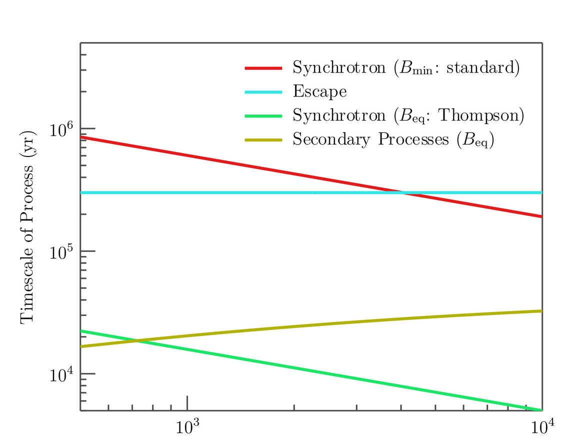
Recent theoretical work advocates the "calorimeter" interpretation of the FIR-radio correlation. Published data and new continuous spectra from the Allen Telescope Array lend support to the theory.

Background

The correlation between the far-infrared (FIR) and radio emission of normal galaxies is **striking for its tightness and the range of conditions in which it holds**. Broadly speaking, emission in both bands traces recent star formation (SF). But the details are unclear: **how is linearity maintained** over such a wide range of conditions?

The **"calorimeter" model** of Völk (1989) posits that correlation holds because radio-emitting electrons cool completely within a small volume. Thompson *et al.* (2006) support the model, arguing that **starburst galaxies have much stronger magnetic fields than commonly assumed**, leading to rapid synchrotron cooling (*below*).

Rough timescales for escape from the galactic disk, synchrotron cooling (minimum-energy and equipartition field cases), and bremsstrahlung and ionization losses ("secondary processes").

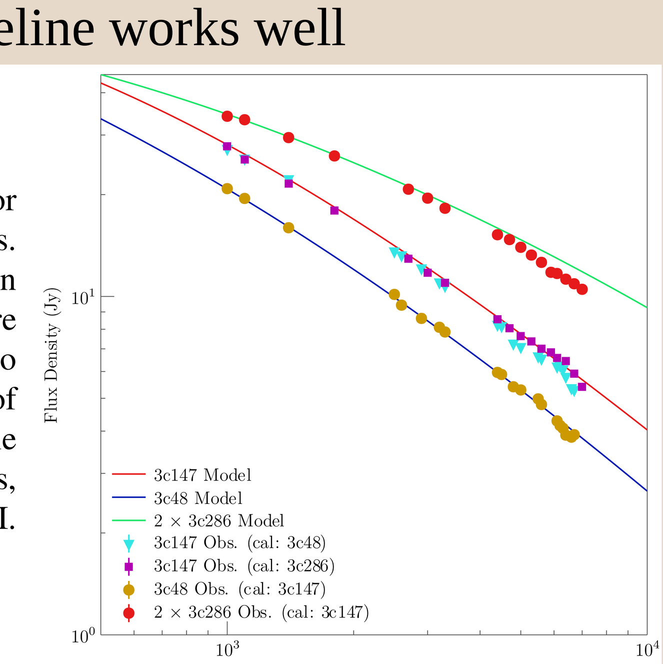


To rebut a common criticism — that **observed galactic spectra are too shallow to be synchrotron-cooled** — Thompson *et al.* consider **ionization and bremsstrahlung losses**, which tend to flatten spectra. Their models **predict deviations from pure power laws** in observed nonthermal spectra. The ATA (Welch *et al.* 2009) is well-suited to testing these predictions.

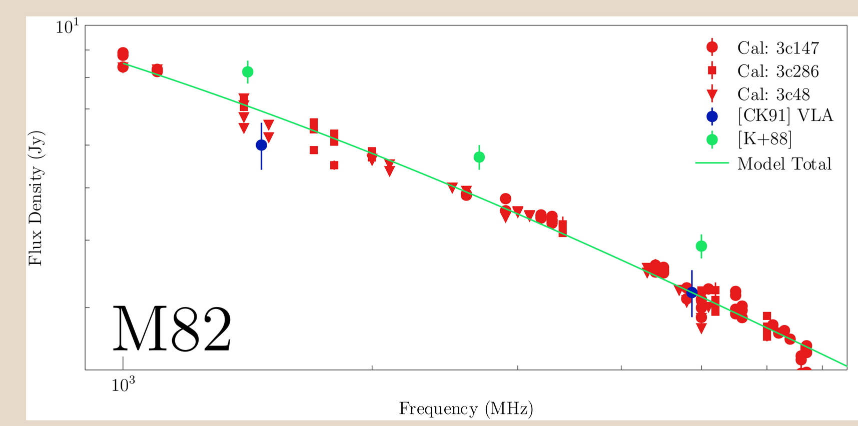
ATA Observations and Data Reduction

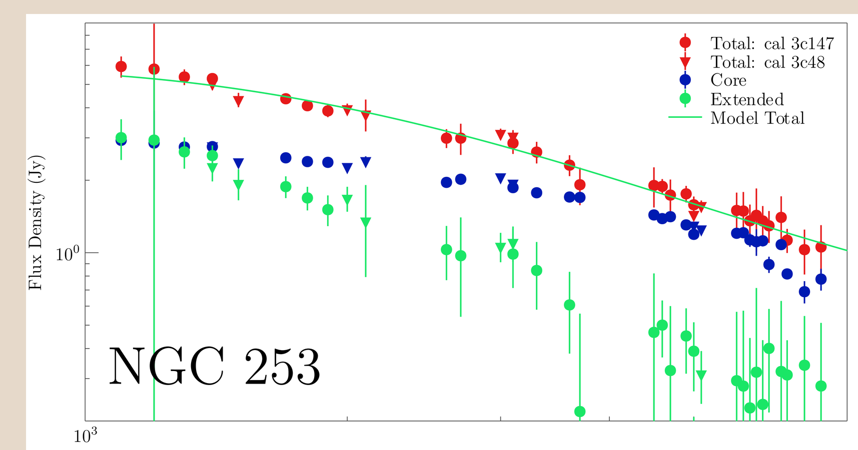
- M82, APG 220, and NGC 253 were observed for 9 hours over 6 epochs in ~1-minute snapshots, with calibrators 3C 48, 3C 147, and 3C 286
- Frequencies ranged from 0.5 GHz to 7 GHz, skipping bands with severe RFI, with a bandwidth of 100 MHz
- Flux calibration was relative to VLA 1999.2 models, which gave the most self-consistent results
- Cross-checks comparing calibrator observations to models (*below*) show the pipeline works well

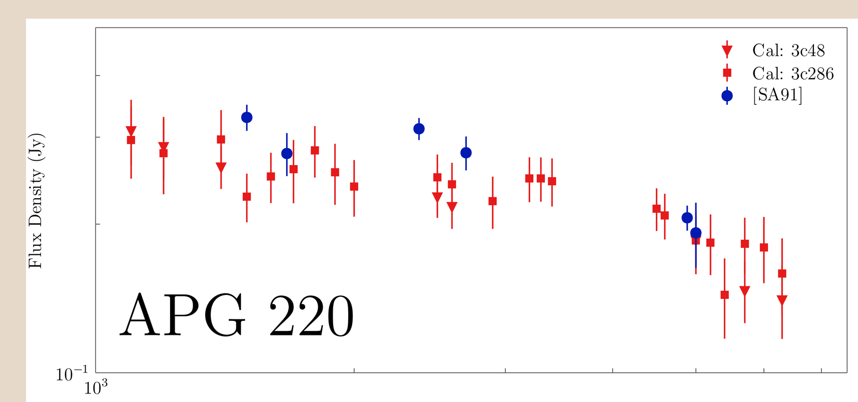
Calibrator cross-checks. Gaps in coverage are mostly due to lack of applicable observations, not RFI.



- Individual scans were processed separately so that repeatability could be assessed
- Reported values are the weighted average of one or more scans
- Observations by the ATA had a **typical snapshot flux precision of 5%** (*right*) varying with source flux
- Results are separated by calibrator so model inaccuracies can be identified

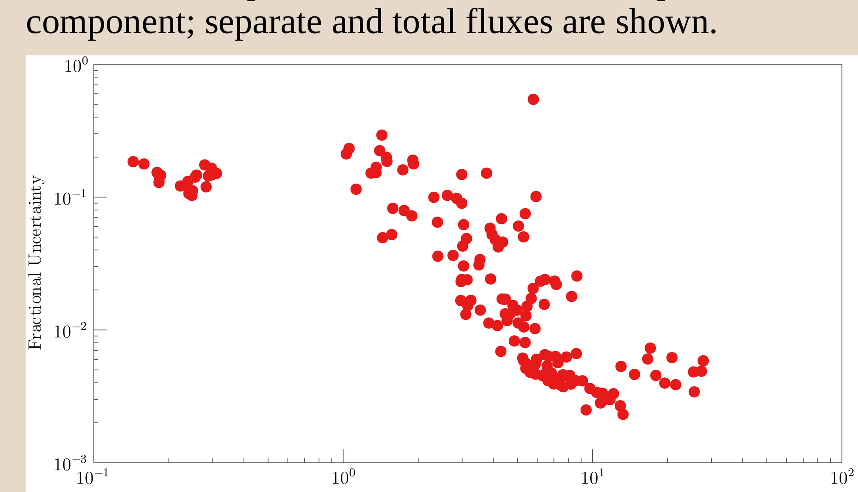






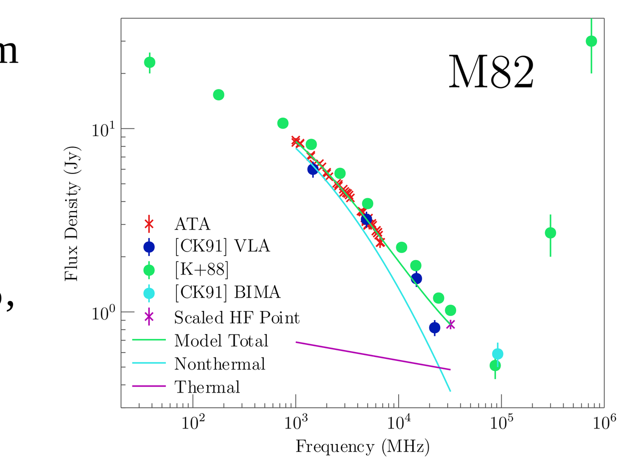
- **The ATA data are presented *above***

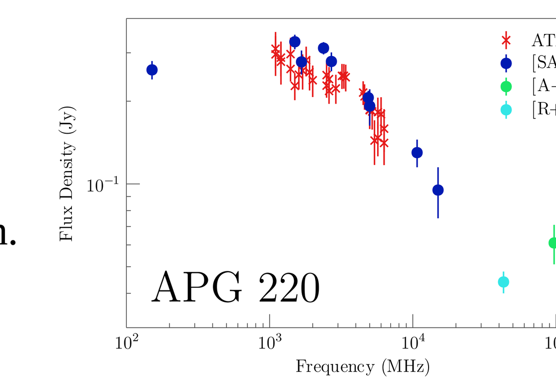
Notes: See *Spectral Modeling* for details on the models. Uncertainties come from the scatter in repeated measurements. For comparison, the M82 plot shows individual scans, not weighted averages. NGC 253 was resolved into a point-source core and an elliptical extended component; separate and total fluxes are shown.

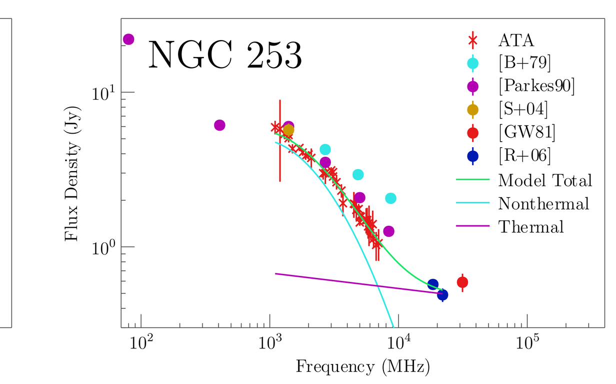


Spectral Modeling

- Models of thermal and nonthermal contributions were fit to the observed spectra and data from the literature.
- The fits to ATA data were augmented with high-frequency points from the literature to better constrain the thermal fraction. For M82, the 32 GHz point was scaled by 86%.
- **ATA fluxes are lower than single-dish measurements,** possibly due to extended emission being resolved out on angular scales of tens of arcmin. ATA and VLA measurements agree well.
- **The best-fit models are shown at *right*.** The data from the literature come from a variety of instruments. The APG 220 ATA data were too noisy to yield useful fits.
- The **formal errors are ~10%,** but these are underestimates due to effects like pointing errors and phase scatter.







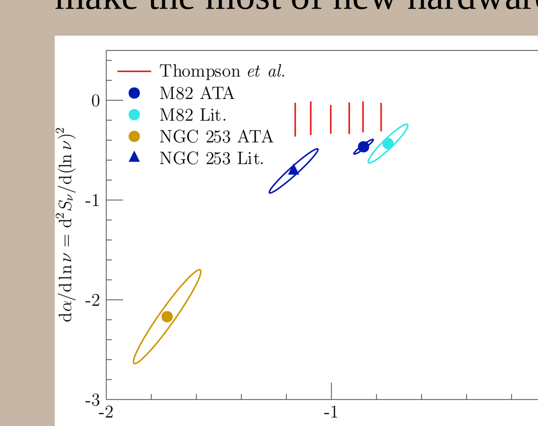
Results and Conclusions

There is **suggestive evidence that the magnetic field $B > B_{min}$** in the observed galaxies, **lending support to the calorimeter model**.

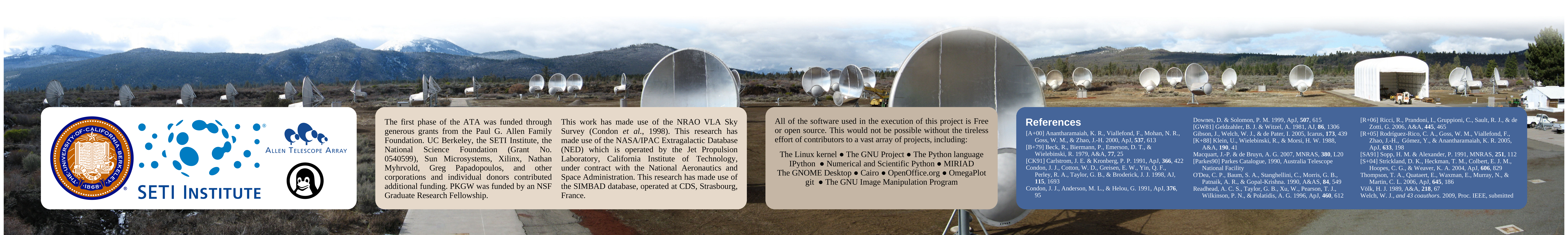
- The **nonthermal spectra steepen in the GHz regime, as predicted in Thompson *et al.*,** although this can be explained in $B = B_{min}$ models.
- Observed **spectral indexes at 5 GHz are consistent with predictions** made by Thompson *et al*. There is significant disagreement at 1 GHz, where free-free absorption may become a factor.
- The **observed spectra steepen more than predicted** (*right*). Solving this discrepancy will be **an important test for the Thompson *et al.* model.**

Future Directions. Other uses for continuous spectra include: **[1]** Obtaining accurate ages and luminosities of gigahertz peaked-spectrum (GPS) sources (*e.g.* O'Dea *et al.* 1990) and compact symmetric objects (CSOs) (*e.g.* Readhead *et al.* 1996). **[2]** Fully characterizing scintillation processes of intraday variables (IDVs) (*e.g.* Macquart & de Bruyn 2007). **[3]** Probing atmospheric chemistry of Jupiter and Saturn (*e.g.* Gibson *et al.* 2005)

Lessons Learned. Experiences relevant to EVLA and SKA: **[1]** Accurate broadband calibrator models are lacking; variability is an issue at higher frequencies. **[2]** Existing visualization and analysis tools have trouble coping with many antennas and spectral channels. New software is *necessary* to make the most of new hardware.



Observed and predicted values of α and dα/d ln ν. The Thompson *et al.* values are computed from simple models with various physically-reasonable parameters.



The first phase of the ATA was funded through generous grants from the Paul G. Allen Family Foundation. UC Berkeley, the SETI Institute, the National Science Foundation (Grant No. 0540599), Sun Microsystems, Xilinx, Nathan Myhrvold, Greg Papadopoulos, and other corporations and individual donors contributed additional funding. PKGW was funded by an NSF Graduate Research Fellowship.

This work has made use of the NRAO VLA Sky Survey (Condon *et al.*, 1998). This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

All of the software used in the execution of this project is Free or open source. This would not be possible without the tireless effort of contributors to a vast array of projects, including:

The Linux kernel • The GNU Project • The Python language
IPython • Numerical and Scientific Python • MIRIAD
The GNOME Desktop • Cairo • OpenOffice.org • OmegaPlot
git • The GNU Image Manipulation Program

References

[A+00] Anantharamaiah, K. R., Viallefond, F., Mohan, N. R., Goss, W. M., & Zhao, J.-H. 2000, ApJ, **537**, 613
[B+79] Beck, R., Biermann, P., Emerson, D. T., & Wielebinski, R. 1979, A&A, **77**, 25
[CK91] Carlstrom, J. E. & Kronberg, P. P. 1991, ApJ, **366**, 422
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, **115**, 1693
Condon, J. J., Anderson, M. L., & Helou, G. 1991, ApJ, **376**, 95
Downes, D. & Solomon, P. M. 1999, ApJ, **507**, 615
[GW81] Geldzahler, B. J. & Witzel, A. 1981, AJ, **86**, 1306
Gibson, J., Welch, W. J., & de Pater, I. 2005, Icarus, **173**, 439
[K+88] Klein, U., Wielebinski, R., & Morsi, H. W. 1988, A&A, **190**, 41
Macquart, J.-P. & de Bruyn, A. G. 2007, MNRAS, **380**, L20
[Parkes90] Parkes Catalogue, 1990, Australia Telescope National Facility
O'Dea, C. P., Baum, S. A., Stanghellini, C., Morris, G. B., Patnaik, A. R., & Gopal-Krishna. 1990, A&AS, **84**, 549
Readhead, A. C. S., Taylor, G. B., Xu, W., Pearson, T. J., Wilkinson, P. N., & Polatidis, A. G. 1996, ApJ, **460**, 612
[R+06] Ricci, R., Prandoni, I., Gruppioni, C., Sault, R. J., & de Zotti, G. 2006, A&A, **445**, 465
[R+05] Rodríguez-Rico, C. A., Goss, W. M., Viallefond, F., Zhao, J.-H., Gómez, Y., & Anantharamaiah, K. R. 2005, ApJ, **633**, 198
[SA91] Sopp, H. M. & Alexander, P. 1991, MNRAS, **251**, 112
[S+04] Strickland, D. K., Heckman, T. M., Colbert, E. J. M., Hoopes, C. G., & Weaver, K. A. 2004, ApJ, **606**, 829
Thompson, T. A., Quataert, E., Waxman, E., Murray, N., & Martin, C. L. 2006, ApJ, **645**, 186
Völk, H. J. 1989, A&A, **218**, 67
Welch, W. J., *and 43 coauthors*. 2009, Proc. IEEE, submitted