CAL-3038

COLUMBIA UNIVERSITY
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COLUMBIA ASTROPHYSICS LABORATORY

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September 9, 1998

Dr. Donald K. West
Mail Code 684.9
NASA Goddard Space Flight Center
Greenbelt, MD 20771

RE: NAG 5-6035

Dear Dr. West:

As required by the terms of my Long-Term Space Astrophysics Research Grant entitled, "Surfing the High Density Universe" (NAG 5-6035), I hereby submit a progress report for year one, covering the period 1 October 1997 through 30 September 1998.

The central theme of the proposed research is to link what we know about galaxy clusters and large-scale structure in the local Universe at $z < 0.1$ to what we know about the original fluctuations that led to this structure as observed in the cosmic microwave background. The simple-minded approach to this question (the kind I always take) is to *look* at structure in the regime $0.1 < z < 1000$. We have a unique resource to help us in this task in the form of the VLA *FIRST* radio survey in which, to date, we have completed mapping nearly 5000 deg^2 of the northern sky to a 20 cm flux density limit of 1.0 mJy. The 435,000 radio sources detected all have positions accurate to better than $1''$. As this report is written, we are obtaining the next $\sim$ 1000 deg^2 of data; the goal of the survey is to complete the full 10,000 deg^2 to be covered in the Sloan Digital Sky Survey.

The *FIRST* radio sources have several advantages for the study of large-scale structure at high redshift: they have a median redshift of $z \sim 1$ (as compared to $z_{med} \sim 0.1$ of the deepest optical galaxy redshift survey to date, the LCRS), they are luminous, and thus visible to $z \sim 5$ at least, and they often contain morphological clues which help in identifying high density regions of the Universe. They are also an extremely pure extragalactic sample ($> 99.9\%$) and, excepting a low-luminosity population arising in star-forming galaxies at low z which can be easily screened out through comparison with optical catalogs of the POSS-I plates, they are all active galactic nuclei, and thus, represent the sites in which massive black holes have already formed (in most models, high density regions).

There are two basic approaches to large-scale structure studies: statistical measures such as the two-point (and higher-order) angular correlation functions, and studies of particular subclasses of objects. We pursue both approaches. We calculated the first significant angular correlation function for a radio survey (Cress et al. 1996) using only the first 1500 deg^2 of thee survey, and plan to explore this further as the database expands. We also began the *FIRST* Bright Quasar Survey (FBQS; Gregg et al. 1996), a continuing project with a number of cosmological implications. Here, I summarize the projects completed under this grant during the past twelve months and offer a brief prospectus on what lies ahead. A bibliography of papers and presentations reporting work supported in whole or

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in part by this grant is attached; nine refereed papers were published or submitted for publication, three conference proceedings were written, and ten talks were given at national and international meetings.

The Geometry of the Universe. It is useful in assessing models for large-scale structure formation to start with the correct geometry for the Universe. In a paper published in February (Buchalter et al. 1998a) we produced the first demonstration using double-lobed radio galaxies that the angular size-redshift relation conforms to the one expected in Friedmann models of the Universe. We calculated the number of sources necessary to constrain tightly the cosmological parameters and thus select amongst the models, and find that 1000 redshifts for bent doubles will be severely constraining even in the presence of size evolution. In that we have more than 10,000 such doubles already in the survey catalog, and have already collected more redshifts than this in the FBQS, this project is tractable. An automated classification algorithm for multiple-component radio sources has been developed, and an initial match with the APM scans of the POSS-I plates for optical identifications has been completed. A detailed plan for implementing this fundamental cosmological measurement will be developed in the coming year.

Higher-order correlation functions. While the pair-wise correlation function has been the most used statistical description of large-scale structure, higher-order correlations are also useful in distinguishing amongst models for structure formation and evolution. Furthermore, the interpretation of the data in terms of such models requires including the nonlinear regime of structure formation (after all, the radio galaxies we see certainly formed on scales smaller than those in which linear regime is applicable). Kamionkowski and Buchalter (1998), Buchalter and Kamionkowski (1998) and Buchalter et al. (1998b) present theoretical work relevant to the interpretation of large-scale structure in the *FIRST* data (Magliocchetti et al 1998 do too, but they were not supported by this grant).

Weak lensing shear. Light from the background radio galaxies reaches Earth only after passing through the foreground distribution of matter, and the lumpy distribution of that matter imposes a distortion on the distribution of the light as a consequence of gravitational lensing. We have begun an ambitious project to detect the effect of this so-called weak lensing shear on *FIRST* sources. While the effect is far too small to see in individual sources, we have shown (Kamionkowski et al. 1998) that the correlation function of the shear signal will be detectable. Since this signal is a consequence of the *total* matter distribtuion, luminous and dark, along the line of sight, it's detection is a powerful constraint on large-scale structure. As in most such analyses, systematic effects are key, and we have been working to understand and eliminate them (Refregier and Brown 1998). A status report on the project is given in Refregier et al. (1998); we expect to be able to complete this project in the coming year.

Bent-double radio galaxies. Relative motion between a dense ambient medium and the host galaxy of a double-lobed radio source will produce bending in the emerging lobes as a consequence of ram pressure on the jets of relativistic plasma. This produces a distinctive C-shape morphology which, we posit, can be used as a tracer of dense intergalactic environments. The fifty-fold improvement in *both* sensitivity and angular resolution the *FIRST*

survey represents means that these sources can be used to find clusters at high redshift. We have demonstrated this in a paper submitted to the ApJ in May. We obtained ~ 20 redshifts for galaxies in the vicinity of each of ten bent-double sources, and found clusters in least eight cases with redshifts ranging from 0.35 to 0.85 (Blanton et al. 1998). We have also started a project to push this technique to higher redshift by obtaining near-IR images of bent doubles which are blank fields to R=23. Of the first three cases examined, one shows a rich cluster in the K-band image with 17 galaxies having $4.5 < (R - K) < 6$ within $1'$ of the radio galaxy; the estimated cluster redshift is $z \sim 1$ (Blanton et al., in preparation).

Radio Clusters. We have refined the technique of selecting clusters of radio sources mentioned in the proposal, and have prepared a list of ~ 50 such groupings ranging in size from $5'$ to $30'$ and containing from 7 to 40 radio sources (all overdensities statistically significant at the 6σ level or greater). Initial optical followup imaging has yielded the surprising result that the sources in these groups appear to have optical counterparts *fainter* than the average *FIRST* source, implying that they are at redshifts > 1. If this is the case, they are enormous structures (~ 1 to 10 Mpc), and may represent the formation of supercluster-scale condensations — just the sort of large-scale structure at intermediate to high redshifts this project hopes to discover. Further followup observations are scheduled for this fall.

Gravitationally lensed quasars. As many authors have shown in the last year, the statistics of gravitationally lensed quasars and studies of individual lensed systems can provide strong cosmological constraints. We have begun a study of FBQS quasars which has already found two lenses (Schechter et al. 1998; Schechter et al., in preparation). Both have now been observed with HST. The first lens has also been monitored for variability to see if it could be used in the time-delay method for deriving the Hubble constant; unfortunately, it appears not to be a highly variable object and so will not be pursued further. We intend to continue this study, as the rate of discovery in our sample is nearly an order of magnitude greater than that in previous lens searches.

AXAF Proposals. One of the main thrusts of this proposal was to use the upcoming suite of new space observatories in the X-ray band in our search for large-scale structure at high redshift. Thus, we prepared two proposals relevant to this work for AXAF Cycle 1. An observation of one of the bent-double clusters was approved for 40 ksec; this will allow us to assess its temperature and luminosity (and therefore its mass). A second proposal was prepared for a public deep survey in the NOAO Deep Field (a *FIRST*-covered region in which very deep seven-color optical/near-IR data is being collected). The specific thrust of our science case was to use the correlation of X-ray background fluctuations with galaxies as a tracer of structure in the Universe. Despite being the highest-rated proposal in its panel, no time was awarded. The proposal may be resubmited in Cycle two in hopes that it will get a lower score and therefore be scheduled.

The coming year. While it is always difficult to predict with precision the future course of research, the following are likely to be included in the activities of the coming year:

- completion of a paper on the highest redshift bent-double cluster
- analysis of AXAF data on one bent-double cluster

- completion of a statistically complete sample of bent-double sources
- identification of the *FIRST* sources in the Postman deep I-band field
- increasing the sample size of radio clusters with optical imaging data
- work aimed at pinning down the redshift distribution of *FIRST* sources
- additional FBQS lensing studies
- completion of weak lensing shear study
- preparation of additional AXAF proposals
- preparation of XMM proposals
- other nifty things I haven't thought of yet because I was writing this report

Please let me know if you require further information on our activities under NAG 5-6035 during its first year.

Sincerely,

David J. Helfand
Professor of Astronomy

Endorsement:

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Sonia C. Park
Projects Officer
Office of Projects & Grants

enclosures:
- List of Publications
- Year 2 Budget

Bibliography for papers published or submitted for publication, and conference presentations, on work supported in whole or in part by NASA grant NAG 5-6035 (1 October 1997 – 30 September 1998).

Refereed Journals

"Interpreting the Clustering of Radio Source," Cress, C.M. and Kamionkowski, M. 1998, MNRAS, 297, 486.

"Constraining Ω_o with the Angular-Size Redshift Relation of Double-Lobed Quasars in the *FIRST* Survey," 1998 Buchalter, Y., Helfand, D.J., Becker, R.H., and White, R.L. 1998, ApJ, 494, 503.

"The First *FIRST* Gravitationally Lensed Quasar: FBQ 0951+2635," Schechter, P., Gregg, M.D., Becker, R.H., Helfand, D.J., and White, R.L. 1998, AJ, 115, 1371.

"Theory and Statistics of Weak Lensing from Large-Scale Structure Mass Inhomogeneities," Kamionkowski, M., Babul, A., Cress, C.M., and Refregier, A. 1998, MNRAS (submitted).

"Effect of Correlated Noise on Source Shape Parameters and Weak Lensing Measurements," Refregier, A., and Brown, S.T. 1998, ApJ (submitted).

"*FIRST* Bent Double Radio Sources: Tracers of High-Redshift Clusters," Blanton, E.L., Gregg, M.D., Helfand, D.J., Becker, R.H., and White, R.L 1998, ApJ. (submitted).

"Weakly Nonlinear Clustering for Arbitrary Expansion Histories," Kamionkowski, M. and Buchalter, A., astro-ph/9807211; submitted to ApJ.

"The Influence of the Power Spectrum and Bias Evolution on the Three-Point Correlation Function," Buchalter, A. and Kamionkowski, M. 1998, submitted to ApJ.

"Angular Clustering in Cold-Dark-Matter Models," Buchalter, A., Kamionkowski, M., and Jaffe, A. 1998, submitted to ApJ.

Conference Proceedings:

"Probing Density Fluctuations Using the *FIRST* Radio Survey." C.M. Cress and the *FIRST* Collaboration 1997, in "Cosmology with the New Radio Surveys", eds. N.Jackson and M.Bremer, (Cambridge University Press: Cambridge) (in press).

"The VLA *FIRST* Survey: Large Scale Structure in the Radio Universe," D.J. Helfand and the *FIRST* Team, in "Cosmology with Wide Field Surveys", eds. S. Colombi and Y. Mellier, 14th IAP Colloquium, (in press).

"Weak Lensing by Large-Scale Structure with the FIRST Radio Survey", A. Refregier, S. Brown, M. Kamionkowski, D.J. Helfand, C. Cress, A. Babul, R.H. Becker, and R.L. White in "Cosmology with Wide Field Surveys", eds. S. Colombi and Y. Mellier, 14th IAP Colloquium, in press.

Talks at conferences:

<u>191^{st} Meeting (January 1998, Washington, DC)</u>

"The Current Status of the VLA *FIRST* Survey," R.H. Becker, D.J. Helfand, and R.L. White, BAAS, 29, 1241.

"Weak Lensing by Large-Scale Structure with the *FIRST* Radio Survey," A. Refregier, S.T. Brown, M. Kamionkowski, C.M. Cress, D.J. Helfand, and A. Babul, BAAS, 29, 1348.

"The *FIRST* Bright Quasar Survey," R.L. White,R.H. Becker, M.D. Gregg, S.A. Laurent-Muehleisen, D.J. Helfand, R.G. McMahon, C.D. Impey, W. Oegerle, and G. Richards, BAAS, 29, 1373.

"Keck II Spectroscopy of Ten New Distant Clusters of Galaxies Associated with Bent-Double Radio Galaxies from the *FIRST* Survey," E.L. Blanton, D.J. Helfand, R.H. Becker, M.D. Gregg, and R.L. White BAAS, 29, 1382.

"Higher-Order Correlation Functions and the *FIRST* Survey," A. Buchalter and M. Kamionkowski, BAAS, 29, 1354.

"The *FIRST*/APM Search for Lensed Radio Lobes," J. Lehar, A. Buchalter, R. McMahon, and C. Kochanek, BAAS, 29, 1307.

192st Meeting (June 1998, San Diego, CA)

"The *FIRST* Faint Quasar Survey," R.H. Becker, S. Laurent- Muehleisen, M. Gregg, M. Brotherton, R.L. White, D.J. Helfand, F. Chaffee,C. Impey, and C. Petry, BAAS (in press).

"The Spectrum of Mass Fluctuations as Derived from the Weak Lensing of *FIRST* Radio Sources," D.J. Helfand, S. Brown, M. Kamionkowski, C. Cress, A. Refregier, R.H. Becker, and R.L. White, BAAS (in press).

14th IAP Metting: Wide Field Surveys in Cosmology (May 1998, Paris, France)

"The VLA *FIRST* Survey: Large Scale Structure in the Radio Universe," D.J. Helfand and the *FIRST* collaboration.

"Weak Lensing Studies with the *FIRST* Survey," A. Refregier and the *FIRST* collaboration.

NASA PROPOSAL BUDGET FORM
LONG-TERM SPACE ASTROPHYSICS PROGRAM

YEAR 2

NAG 5-6035

Principal Investigator	Institution	Proposal Title
David J. Helfand	Columbia University	Surfing the High Density Universe

A. Salaries, Senior Personnel	Monthly or Hourly Rate	No. of Months	Funds Grant Year 1	Funds Grant Year 2	Funds Grant Year 3	Funds Grant Year 4	Funds Grant Year 5
1. PI David J. Helfand, Prof. of Astronomy	10,296	1.5		15,444			
2. Co-I							
3. Co-I							
4. Co-I							
B. Salaries or Wages, Other Personnel (show numbers in parentheses)							
1. (1) Post Doctoral Associates	3,400/mo.	6.5		22,100			
2. (1) Other Professionals (Technicians, Programmers, etc.)	4,100/mo.	1		4,100			
3. (1) Clerical Admin. Coord. for (.25 mos.)				900			
4. (2) Other (specify) 2 Undergraduates: Summer				5,200			
2 Undergraduates: Academic Year				5,304			
Total Salaries				53,048			
C. Fringe Benefits (if charged as direct costs; specify) 28.4% of salaries**				12,506			
Total Salaries, Wages, and Fringe Benefits (A+B+C)				65,554			
D. Permanent Equipment, incl. Workstation (list each item > $5000; continue on separate sheet if necessary)							
1 Nine Gbyte Disk @ 2,500 (Yr. 2)				2,500			
Total Permanent Equipment				2,500			
E. Travel, Domestic (incl. Canada, U.S. Possessions) AAS Meetings and Various Science Centers (AXAF,XMM,ASTRO-E)				2,588			
Travel, Foreign International Meeting							
F. Other Direct Cost							
1. Materials and Supplies							
2. Publication Costs 3 papers/12 pgs. each @ 135/per page + 3 sets 50 reprints @ 97 ea.				5,151			
3. Computer Services (rate/hr)							
4. Subgrants/Contracts (specify)							
5. Other (specify) Exabyte Tapes 30/yr @ 11/ea. (330); Telecommunication (300); Reproduction (300)							
Mailings (322)				1,252			
G. Total Direct Cost (A through F)				77,045			
H. Indirect Costs (specify)							
70.5% of all direct costs excluding permanent equipment.				52,554			
I. Total (G+H)				129,600			

PI (signature) David J. Helfand

129,600

Cognizant Institutional Officer (typed name and signature)
Sonia C. Park

Position/Title
Projects Officer, Office of Projects and Grants

Address and Tel. No. of Institution's Sponsored Research Office
351 Engineering Terrace, Columbia University, New York, NY 10027

**Undergrad salaries are not charged fringe during acad. yr.; 8.15% is charged during summer mos.

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