How I Found My Place in the Universe (and helped everybody else find theirs)

By Jessica Mink
Smithsonian Astrophysical Observatory

American Museum of Natural History, April 13, 2015
Outline

Planet Surfaces: 1973-4 Mars Observations

Stars and Planets: 1976-1990 Occultations

Milky Way: 1985-1990 IRAS and Spacelab 2 IRT

The Universe: 1990-2015 WCS, Plates, and Spectroscopy

American Museum of Natural History, April 13, 2015
Projections

Orthographic: Face-on planet in sky
Mercator: Map of entire planet surface
It All Started With Mars

MIT Vidicon Spectrometer with camera monitoring slit in mirror

Spectrometer slit reprojected across Mercator projection of Mars surface

(Mink, MIT S.M. Thesis 1974)
It All Started With Mars

Aperture photos projected on observed planet disk and reprojected onto Mercator projection of Mars

(Mccord, Huguenin, Mink, and Pieters, Icarus 31, 1977)
Then Came Uranus

Occultation of SAO 158687 by Uranus and Its Rings

(Eliot, Dunham, and Mink, Nature 261, 328, May 26 1977)
Mapping observability

Geocentric prediction of Uranus 16

Sun down, Uranus up for Uranus 16
Finding Stars to be Occulted

Map showing appulse of the Pluto/Charon system to a star
Note rotation of Charon around Pluto and variations in star position
Predicting Occultations

Palomar Sky Survey overlay for stars occulted by Uranus

Sky plane map of Uranus ring occultation of KMU102
Predicting Occultations

Venus Occultation of SAO 160149 on January 21, 2003

Click here for predictions for various cities

Catalog positions at 2003-01-21 11:00 UT
The arcsec column gives the distance from the SAO position

<table>
<thead>
<tr>
<th>Catalog Number</th>
<th>RA(J2000)</th>
<th>Dec(J2000)</th>
<th>Mag</th>
<th>Type</th>
<th>Arcsec</th>
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<td>160149</td>
<td>16:54:16.4</td>
<td>-19:18:18.4</td>
<td>8.20</td>
<td>50</td>
<td>1.60</td>
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<tr>
<td>252200</td>
<td>16:54:58.3</td>
<td>-19:18:48.3</td>
<td>8.60</td>
<td>60</td>
<td>2.87</td>
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<tr>
<td>Tycho2</td>
<td>16:54:55.9</td>
<td>-19:18:53.0</td>
<td>9.14</td>
<td></td>
<td>5.57</td>
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</table>

The following positions are at the catalog epochs

<table>
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<tr>
<th>Catalog Number</th>
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<th>Dec(J2000)</th>
<th>Mag</th>
<th>Class</th>
<th>Band</th>
<th>Arcsec</th>
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<tbody>
<tr>
<td>6226</td>
<td>16:54:50.9</td>
<td>-19:18:10.4</td>
<td>8.51</td>
<td>6</td>
<td>B</td>
<td>1.28</td>
</tr>
<tr>
<td>GSC ACTnum</td>
<td>16:54:50.9</td>
<td>-19:18:10.4</td>
<td>8.51</td>
<td>6</td>
<td>B</td>
<td>1.28</td>
</tr>
<tr>
<td>2MASS</td>
<td>16:54:50.9</td>
<td>-19:18:10.4</td>
<td>8.51</td>
<td>6</td>
<td>B</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Finding Charts

Click for larger map of Venus occultation of SAO position

Click for larger map of Venus occultation of PPM position

Click for larger map of Venus occultation of Tycho-2 position

Click for larger map of 5th field around star
Click for larger map of 1st field around star
IRAS Projections

Edited by C.A. Beichman, G. Neugebauer, H.J. Habing, P.E. Clegg, T.J. Chester
X. The Formats of the IRAS Catalogs and Atlases, D. Extended Emission

Polar: Maps of sky around North and South Poles

Aitoff: Map of entire sky

Sinusoidal: Maps of galactic plane

Gnomonic: Maps of regions of sky
All-Sky IR Mapping from Space

Spacelab 2 Infrared Telescope
(Space Shuttle Challenger, July 1985)
All Sky IR Mapping from Space

IRAS 120 μm
Aitoff All-Sky Projection
1984 Data Release HCON 1
All Sky IR Mapping from Space

COMMENT  PROJECTION FORMULAE:
COMMENT  FORWARD FORMULA; XLON0 IS THE CENTER LONGITUDE OF THE
COMMENT   MAP. ARC-SINE AND ARC-COSINE FUNCTIONS ARE REQUIRED.
COMMENT  R2D = 45. / ATAN(1.)
COMMENT  PIX = 2.
COMMENT  RHO = ACOS( COS(XLAT) * COS((XLON-XLON0)/2.) )
COMMENT  THETA = ASIN( COS(XLAT) * SIN((XLON-XLON0)/2.) / SIN(RHO) )
COMMENT  F = 2. * PIX * R2D * SIN(RHO/2.)
COMMENT  SAMPLE = -2. * F * SIN(THETA)
COMMENT  XLINE = -F * COS(THETA)
COMMENT  IF(XLAT .LT. 0.)  XLINE = -XLINE
COMMENT

COMMENT  REVERSE FORMULA; XLON0 IS THE CENTER LONGITUDE OF THE MAP.
COMMENT   ARC-SINE AND ARC-COSINE FUNCTIONS NEEDED.
COMMENT  R2D = 45. / ATAN(1.)
COMMENT  PIX = 2.
COMMENT  Y = -XLINE / (PIX * 2. * R2D)
COMMENT  X = -SAMPLE / (PIX * 2. * R2D)
COMMENT  A = SQRT(4.-X*X-4.*Y*Y)
COMMENT  XLAT = R2D * ASIN(A*X/(2.*COS(XLAT)))
COMMENT  XLON = XLON0 + 2. * R2D * ASIN(A*X/(2.*COS(XLAT))))
COMMENT
COMMENT  REFERENCES:
COMMENT   IRAS SDAS SOFTWARE INTERFACE SPECIFICATION(SIS) #623-94/NO. SF05
COMMENT   ASTRON. ASTROPHYS. SUPPL. SER. 44,(1981) 363-370 (RE:FITS)
COMMENT   RECONCILIATION OF FITS PARM S W/ SIS SF05 PARM S:
COMMENT   NAXIS1 = (ES - SS + 1); NAXIS2 = (EL - SL + 1);
COMMENT   CRPIX1 = (1 - SS);   CRPIX2 = (1 - SL)

IRAS  Aitoff All-Sky Projection Fortran Code in FITS Header
All Sky IR Mapping from IRT

1985 Day 213, Orbit 4, 50,964 0.1-sec frames

Spacelab 2 Infrared Telescope
(Space Shuttle Challenger, July 1985)
Galactic Center from Spacelab 2

FIG. 5.—Contour map of the 2.4 $\mu$m emission from the Galactic plane region. The contours are spaced logarithmically in 10 steps between $0.67 \times 10^{-10}$ and $16 \times 10^{-10}$ W cm$^{-2}$ $\mu$m$^{-1}$ sr$^{-1}$.

Linear Projection in Galactic Coordinates
(Kent, Mink, Fazio, Koch, Melnick, Tardiff, Maxson, ApJS 78:403-408, 1992)
Galactic Center from Spacelab 2

Linear Projection in Galactic Coordinates
(Mink, August 1990, unpublished)
All-Sky Maps meet Catalogs
All-Sky Maps meet Catalogs

Space Telescope Guide Star Catalog, Galactic Plane, Aitoff Projection
Owen Gingerich will present a keynote address at a conference sponsored by the American Academy of Rome celebrating the moment in 1611 when Galileo Galliei proudly presented the "telescope" to the intelligentsia of Rome... the Academy asked Paine Professor of Astronomy and director of the Harvard-Smithsonian Center for Astrophysics Irwin Shapiro and his Center colleague Douglas Mink to produce a map of the stars as they appeared over Rome on the night of April 14, 1611. For their efforts, Shapiro and Mink received a Jeroboam of champagne; Gingerich, however, got a trip to Rome. (Harvard Gazette, April 10, 1997)
Onto the World Wide Web

The Smithsonian Astrophysical Observatory (SAO) is part of the Harvard–Smithsonian Center for Astrophysics in Cambridge, Massachusetts. The SAO/TDC creates and maintains software to process and archive data from optical and infrared telescopes in Harvard, Massachusetts and on Mt Hopkins in Arizona.

The SAO TDC distributes several pieces of software:
- RVSAO: an IRAF package for finding radial velocities from spectra
- RGSC: a program for searching the Hubble Space Telescope Guide Star Catalog.
- SKYMAP: a program for mapping star catalogs onto the sky

The staff of the TDC are:
- Doug Mink, software developer
- Mike Kurtz, software philosopher

Astronomical Software Elsewhere

Other Astronomical Resources

Navigating the Internet

A useful introduction to the World–Wide Web (WWW) is available from NASA/Goddard.

Last updated 12 November 1993
SKYMAP is an astronomical mapping program written in Fortran and C for Unix workstations by Doug Mink of the Smithsonian Astrophysical Observatory Telescope Data Center. If you just need positions, several other options are available. The WCSTools package contains C programs which can search the GSC, USNO, and SAO catalogs, among others. The obsolete programs, rgsc for the Guide Star Catalog and star and its variants for other catalogs, use the same Fortran and C code as skymap.

**Manual**

**Examples** [Grid] [Guide Stars] [New Field] [Field from catalog]

**Commands** [Command Line] [Menu] [Cursor]

**Installation**

**Parameters:** [Dictionary] [Format]

**Catalogs** [ASCII] [Binary]

**Reference** D.Mink(1993), ADASS II [full text]

**Notes**

**Versions**

Last updated 3 April 2003 by Doug Mink, dmink@cfa.harvard.edu
Digitized Sky Survey Projection


PLTLABEL= 'E1356 ' /Observatory plate label
PLATEID = '08MC ' /GSSS Plate ID
REGION = 'XE429 ' /GSSS Region Name
DATE-OBS= '23/03/55 ' /UT date of Observation
UT = '06:02:00.00 ' /UT time of observation
EPOCH = 1.9552226562500E+03 /Epoch of plate
PLTRAH = 10 /Plate center RA
PLTRAM = 7 / PLTRAS = 5.5528480000000E+01 /
PLTDECN = '+ ' /Plate center Dec
PLTDECD = 17 /
PLTDECM = 17 /
PLTDECS = 3.8380860000000E+01 /
EQUINOX = 2.0000000000000E+03 /Julian Reference frame
equinox
EXPOSURE= 5.0000000000000E+01 /Exposure time minutes
BANDPASS= 8 /GSSS Bandpass code
PLTGRADE= 1 /Plate grade
PLTSCALE= 6.7200000000000E+01 /Plate Scale arcsec per mm
SITELAT = '+33:24:24.00 ' /Latitude of Observatory
SITELONG= '-116:51:48.00 ' /Longitude of Observatory
TELESCOP= 'Palomar 48-inch Schmidt' /Telescope where plate taken
CNPIX1 = 10748 /X corner (pixels)
CNPIX2 = 2023 /Y corner
DATATYPE= 'INTEGER*2 ' /Type of Data
XPIXELSZ= 2.5284450000000E+01 /X pixel size microns
YPIXELSZ= 2.5284450000000E+01 /Y pixel size microns

PPO1 = 0.0000000000000E+00 /Orientation Coefficients
PPO2 = 0.0000000000000E+00 /
PPO3 = 1.7747471555000E+05 /
PPO4 = 0.0000000000000E+00 /
PPO5 = 0.0000000000000E+00 /
PPO6 = 1.7747471555000E+05 /

AMDX1 = 6.7241844402360E+01 /Plate solution x coefficients
AMDX3 = -2.0498717200880E+02 /
AMDX4 = -1.3607216770700E-05 /
AMDX5 = -2.2201873529570E-05 /
AMDX6 = 7.4284599162830E-07 /
AMDX7 = 0.0000000000000E+00 /
AMDX8 = 1.9162087720540E-06 /
AMDX9 = -9.2146076762020E-10 /
AMDX10 = 2.1089546241680E-06 /
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AMDX1 = 6.7241844402360E+01 /Plate solution x coefficients
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AMDX9 = -9.2146076762020E-10 /
AMDX10 = 2.1089546241680E-06 /
AMDX11 = -9.3945135632070E-08 /
Digitized Sky Survey Projection


DS9 display of DSS image with previous header

DS9 display of same DSS image with regions generated by WCSTools imcat program which remotely accessed the GSC2 catalog
AIPS Projections

The eight most commonly-used projections of classic AIPS may be computed using the *worldpos* and *worldpix* subroutines written by Bill Cotton and Eric Greisen of NRAO:

- **SIN**: Orthographic projection
- **TAN**: Tangent plane projection
- **ARC**: Zenithal equidistant projection
- **NCP**: North celestial pole projection
- **GLS**: Sanson-Flemsteed sinusoidal projection
- **MER**: Mercator projection
- **AIT**: Hammer-Aitoff equal area all-sky projection
- **STG**: Stereographic projection (zenithal orthomorphic)

FITS-WCS Projections


AZP: Zenithal (Azimuthal) Perspective  
SZP: Slant Zenithal Perspective  
TAN: Gnomonic = Tangent Plane  
SIN: Orthographic/synthesis  
STG: Stereographic  
ARC: Zenithal/azimuthal equidistant  
ZPN: Zenithal/azimuthal PolyNomial  
ZEA: Zenithal/azimuthal Equal Area  
AIR: Airy  
CYP: CYlindrical Perspective  
CAR: Cartesian  
MER: Mercator  
CEA: Cylindrical Equal Area  
COP: COnic Perspective

COD: COnic equiDistant  
COE: COnic Equal area  
COO: COnic Orthomorphic  
BON: Bonne  
PCO: Polyconic  
SFL: Sanson-Flamsteed  
PAR: Parabolic  
MOL: Mollweide  
CSC: COBE quadrilaterialized Spherical Cube  
QSC: Quadrilateralized Spherical Cube  
TSC: Tangential Spherical Cube  
NCP: North celestial pole (special case of SIN)  
GLS: GLobal Sinusoidal (Similar to SFL)
Fitting a WCS using WCSTools

USNO-B1.0 Catalog plotted over image using telescope pointing

FITS header with limited WCS keywords from telescope
Fitting a WCS using WCSTools

USNO-B1.0 Catalog plotted over image after imwcs WCS fit

FITS header with WCS keywords after WCS fit using imwcs
Finding Stars for WCSTools

WCSTools supports several ways to find the star-like objects in an image

- WCSTools IMSTAR task (also built into IMWCS)
- IRAF DAOFIND task (its X,Y,Magnitude is WCSTools standard position format)
- Sextractor (output formattable to WCSTools standard)
# More Catalogs

These catalogs are available and supported by [SAO/TDC search and mapping software](https://www.astro.washington.edu/cgi-bin/ticdata-form.pl).

<table>
<thead>
<tr>
<th>Catalog or Format</th>
<th>No. of Stars</th>
<th>Bytes</th>
<th>Region Search</th>
<th>Image Search</th>
<th>Mapping</th>
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<td>1,036,968,787</td>
<td>83,614,080,960</td>
<td>sub1 (scat)</td>
<td>inub1 (imcat)</td>
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<td>GSC II Catalog (2.2.01)</td>
<td>998,402,801</td>
<td>&gt;80,000,000,000</td>
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<td>ingsc2 (imcat)</td>
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<td>11,533,193</td>
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<td>inucac3 (imcat)</td>
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<td>USNO UCAC2 Catalog</td>
<td>48,366,996</td>
<td>2,128,147,841</td>
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<td>GSC ACT Catalog</td>
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<td>1,231,787,520</td>
<td>gscact (scat)</td>
<td>ingsca (imcat)</td>
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<td>SDSS Photometry Catalog</td>
<td>53 million (DR1)</td>
<td>??</td>
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<td>inssds (imcat)</td>
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<td>HST Guide Star Catalog</td>
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<td>gsc (scat)</td>
<td>ingsca (imcat)</td>
<td>skmap</td>
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<td>Tycho-2 Catalog</td>
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<td>528,721,576</td>
<td>sty2 (scat)</td>
<td>inty2 (imcat)</td>
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<td>USNO/Hipparcos ACT Catalog</td>
<td>988,758</td>
<td>318,380,076</td>
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<td>inmac (imcat)</td>
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<td>SKY2000 Catalog</td>
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<td>skmap</td>
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<td>PPM Catalog</td>
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<td>22,734,656</td>
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<td>mppm (imcat)</td>
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<td>SAO Catalog</td>
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<td>skmap</td>
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<td>skmap</td>
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<td>449,2312</td>
<td>ship (scat)</td>
<td>inhip (imcat)</td>
<td>skmap</td>
</tr>
<tr>
<td>Yale Bright Star Catalog</td>
<td>3256</td>
<td>291,548</td>
<td>ehbc (scat)</td>
<td>inhebc (imcat)</td>
<td>skmap</td>
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<tr>
<td>Starbase tab-delimited ASCII</td>
<td>varies</td>
<td>varies</td>
<td>scat</td>
<td>incat</td>
<td></td>
</tr>
<tr>
<td>TDC Space-Delimited ASCII</td>
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<td>varies</td>
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<td>incat</td>
<td>skmap</td>
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<tr>
<td>TDC Binary</td>
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<td>incat</td>
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<td>inu2 (imcat)</td>
<td>skmap</td>
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<td>55,988,299</td>
<td>664,418,868</td>
<td>susan2 (scat),</td>
<td>inusn2 (imcat)</td>
<td>skmap</td>
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<tr>
<td>USNO-A1.0 Catalog</td>
<td>488,000,850</td>
<td>5,856,022,320</td>
<td>suan1 (scat),</td>
<td>inu1 (imcat)</td>
<td>skmap</td>
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<tr>
<td>USNO-SA1.0 Catalog</td>
<td>54,787,624</td>
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<td>susan1 (scat),</td>
<td>inusn1 (imcat)</td>
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<tr>
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<td>19,911,514</td>
<td>238,638,168</td>
<td>sujp (scat),</td>
<td>inuj (imcat)</td>
<td>skmap</td>
</tr>
</tbody>
</table>
Testing Catalog Accuracy

216 1x1 degree fields from the 8K array on the KPNO 36-inch telescope cover half of the CfA Century survey, 50 degrees across the sky.
Testing Catalog Accuracy

The 2MASS Point Source Catalog plotted over one of the 1728 test images
Testing Catalog Accuracy

Astronomical Data Analysis Software and Systems XIII, F. Ochsenbein, M. Allen,
and D. Egret, eds. ASP Conference Series, Vol. 314, p. 141

Differences between catalogs and WCS fits to 1726 images
Testing Catalog Accuracy

D. J. Mink (2010) Unpublished

Differences between catalogs and WCS fits to 1726 images
Accommodating image distortions in WCSTools

WCSTools supports several methods of fitting distortions to images as this seems not to be standardizable:

- Digitized Sky Survey Plate Model
- IRAF TNX and ZPX projections with polynomial distortion
- Spitzer/STScI polynomial distortion model
- SWARP polynomial distortion model
Putting Positions on Harvard's Plates


From handwritten cards and logbooks
Putting Positions on Harvard's Plates


From three floors of cabinets of glass plates
Putting Positions on Harvard's Plates

From glass to bytes on home-built scanner
Putting Positions on Harvard's Plates

M44 in Plate MC21438

M44 in Plate MC21438 with Tycho 2 Catalog stars marked

Zoom in and overplot stars using WCS
Putting Positions on Harvard's Plates

100,000th Plate Scanned, April 7, 2015
**sethead** sets values of keywords in FITS Headers

Each keyword should be followed by an equal sign and the value to which it is to be set.

Values which are all numeric are assumed to be numbers and are aligned as such within the header.

A list of filenames may be used by prefacing the name of the file containing the list with a @.

Multiple FITS extension headers may be changed at once using -x [range of extension numbers]

---

Change the right ascension and declination of a FITS image to a different epoch.

**Before:**

RA      = '9:51:19.45'         /MEAN RA
DEC     = '69:15:26.42'        /MEAN DEC
EPOCH   = 1950                 /MEAN EPOCH


SETHEAD WCSTools 3.9.1, 24 March 2015, Jessica Mink (jmink@cfa.harvard.edu)
Set Header Parameter Values in FITS image file test.fts
RA = 09:55:25.177
DEC = +69:01:13.72
EPOCH = 2000
teste.fts: rewritten successfully.

**After:**

XRA     = '9:51:19.45'         /MEAN RA
XDEC    = '69:15:26.42'        /MEAN DEC
XEPOCH  = 1950                 /MEAN EPOCH

...
gethead extracts information from FITS headers

Keyword names may be entered in either upper or lower case

Tab-separated table output, with column headers, is an option

A file containing a list of filenames may be used by prefacing it with a @.

Multiple parameters from list of FITS files

Get the image sizes from the NAXIS, NAXIS1, and NAXIS2 header keywords from a list of FITS and IRAF files, printing the output in tab table format:

```
$ gethead -th @fits.list naxis naxis1 naxis2
FILENAME        NAXIS   NAXIS1  NAXIS2
--------        -----   ------  ------
0083.19083010-0706459.fits      2       2720    161
hiptest.fits    2       600     600
 test.fits      2       2720    161
test_fabien.fits 2       2080    2048
testbin.fits    2       765     510
testbinf.fits   2       680     450
testbinfg10x10.fits 2       765     510
testbinfg20x20.fits 2       765     510
testbinfg40x40.fits 2       680     450
webccd-1.fits   2       680     450
webccd-2.fits   2       765     510
```
Redshifting Into the Universe

Before Sky Removal

After Sky Removal

12,553 Spectra from the Hectospec SHELS survey