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Hubble Space Telescope multi-color ACS mosaic of M51, the Whirlpool Galaxy

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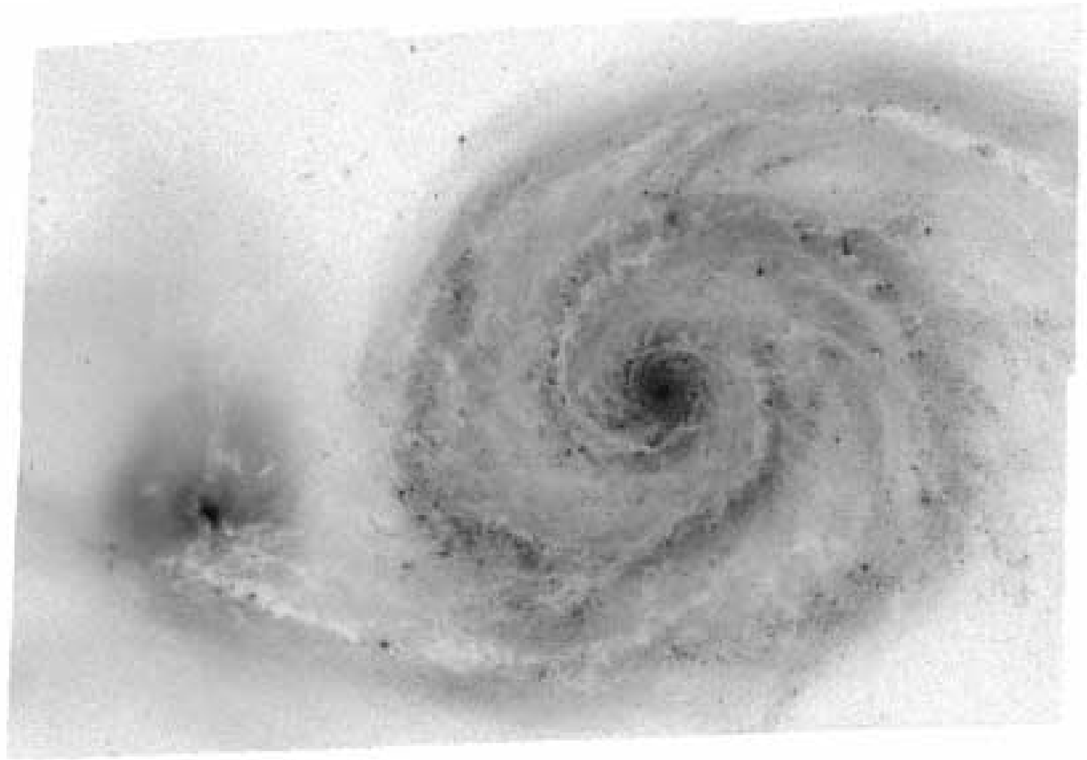


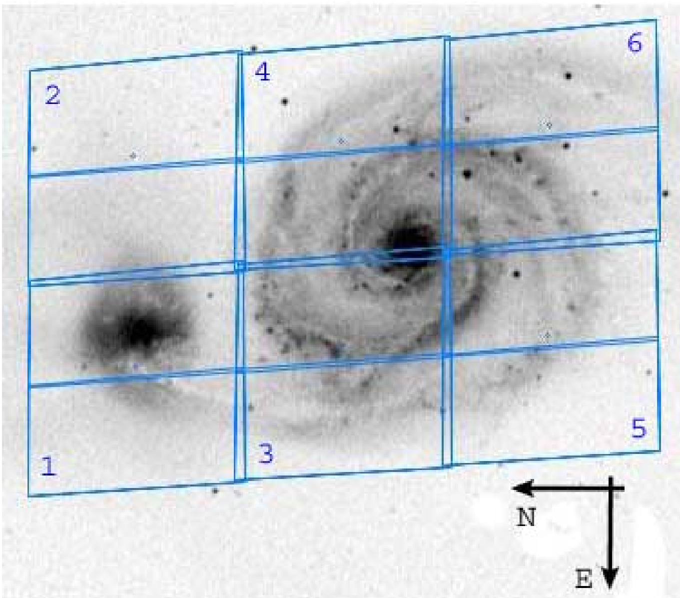
(a) B-band (F435W) mosaic of M51

Abstract

In January 2005, the Hubble Heritage Team obtained a large 4-color (B, V, I, and Hα) mosaic image of the Whirlpool Galaxy NGC 5194 (M51), and its companion NGC 5195, with the Advanced Camera for Surveys (ACS) onboard the *Hubble Space Telescope* (HST). The resulting color composite image was released to the community on April 25, 2005, to celebrate Hubble's 15th anniversary. Cycle 14 HST proposers were encouraged to submit General Observer (GO) and Archival Research (AR) proposals to complement and/or analyze this unique dataset. Since our M51 mosaics represent a significant investment of expert processing beyond the standard archival products, we have also released our drizzle-combined FITS data as a High-Level Science Product via the Multimission Archive at STScI (MAST). This paper documents the key aspects of the observing program and image processing: calibration, image registration and combination (drizzling), and the rejection of cosmic rays and detector artifacts. Our processed FITS mosaics can be downloaded from:
http://archive.stsci.edu/prepds/m51/

1. Introduction

Our observing program (HST proposal 10452; PI Beckwith) produced 96 individual exposures with the ACS Wide Field Channel (WFC). For each of the four filters (Johnson B,V,I, and Hα), four exposures were obtained at six slightly overlapping pointings or "tiles" in a 2x3 mosaic, at a telescope orientation of ˜270 degrees (see Figure b).



(b) The six primary pointing positions or "tiles" (Digitized Sky Survey image with apertures overlayed in the Visual Target Tuner)

The exposure times for each filter are summarized in Table 1. The four exposures within each tile were dithered: a small sub-pixel dither (2.5 x 1.5 pixels), with a larger dither which spans the interchip gap (5x60 pixels). For more on ACS dither patterns, see:
http://www.stsci.edu/hst/acs/proposing/dither/ACS-WFC-DITHER-LINE.html

Table 1: Exposure times by filter

Filter	Exposure time	Limiting mag
F435W (B)	4 x 680s = 2720s	27.3 mB
F555W (V)	4 x 340s = 1360s	26.5 mV
F814W (I)	4 x 340s = 1360s	25.8 mI
F658N (Hα, [N II])	4 x 680s = 2720s	-

2. Data calibration and registration

The standard archival data was retrieved "on-the-fly" from MAST, after the best calibration reference files became available, and with standard ACS pipeline (CALACS) processing: e.g. bias, dark, and flat-field corrections. The calibration reference files also propagate data quality flags which identify many types of detector artifacts – most of which were excluded during `MultiDrizzle` processing (described below). These include bad CCD columns, hot pixels (and their CTE tails), warm pixels, and saturated pixels, etc. For further details of standard calibrations, see the ACS Data Handbook, (Pavlovsky et al. 2005). The latest calibration reference files, and definitions of data quality flags are available on the ACS website:
http://www.stsci.edu/hst/acs/analysis/reference_files

As input to the drizzle-combination described below, we used the flat-fielded images (`*_flt.fits` or hereafter simply `flt`). Since this dataset is not associated, the pipeline currently generates single-image drizzled output (`*_drz.fits`) for each exposure. Although `MultiDrizzle` was added to the ACS pipeline in 2004, it can only combine associated datasets, and even then, it could not assemble large mosaics (which are essentially an association of associations), since they would produce prohibitively large output files. In the standalone environment, however, `MultiDrizzle` can combine any set of images, generating it's own association table (`*_asn.fits`) for all the input exposures. Note that this table also gets updated with the shifts and rotations provided in the `shiftfile` (to register the mosaic, as described below). Here is the I-band association table generated by `MultiDrizzle`:

```
# Table f814w/h_m51_i_s05_asn.fits[1] Wed 10:49:34 20-Apr-2005
# row MEMNAME      MEMTYPE  XDELTA  YDELTA  ROTATION
#                           pixels  pixels   degrees
    1  j97c11kdq    EXP-DTH   -8.1    11.4     0.003
    2  j97c12klq    EXP-DTH   -8.1    11.4     0.003
    3  j97c13nmq    EXP-DTH   -8.1    11.4     0.003
    4  j97c14ryq    EXP-DTH   -8.1    11.4     0.003
    5  j97c21h4q    EXP-DTH   -1.9     7.6     0.000
    6  j97c22uwq    EXP-DTH   -1.9     7.6     0.000
    7  j97c23zrq    EXP-DTH   -1.9     7.6     0.000
    8  j97c24mxq    EXP-DTH   -1.9     7.6     0.000
    9  j97c31ruq    EXP-DTH    0.0     0.0     0.000
   10  j97c32uwq    EXP-DTH    0.0     0.0     0.000
   11  j97c33obq    EXP-DTH    0.0     0.0     0.000
   12  j97c34xeq    EXP-DTH    0.0     0.0     0.000
   13  j97c41xmq    EXP-DTH   -5.3    16.4     0.001
   14  j97c42xuq    EXP-DTH   -5.3    16.4     0.001
   15  j97c43n5q    EXP-DTH   -5.3    16.4     0.001
   16  j97c44ndq    EXP-DTH   -5.3    16.4     0.001
   17  j97c51r6q    EXP-DTH    1.1    -2.5   359.998
   18  j97c52uoq    EXP-DTH    1.1    -2.5   359.998
   19  j97c53v4q    EXP-DTH    1.1    -2.5   359.998
   20  j97c54vcq    EXP-DTH    1.1    -2.5   359.998
   21  j97c61hcq    EXP-DTH    7.6     6.5     0.000
   22  j97c62y2q    EXP-DTH    7.6     6.5     0.000
   23  j97c63req    EXP-DTH    7.6     6.5     0.000
   24  j97c64rmq    EXP-DTH    7.6     6.5     0.000
   25  h_m51_i_s05  PROD-DTH   0.0     0.0     0.000
```

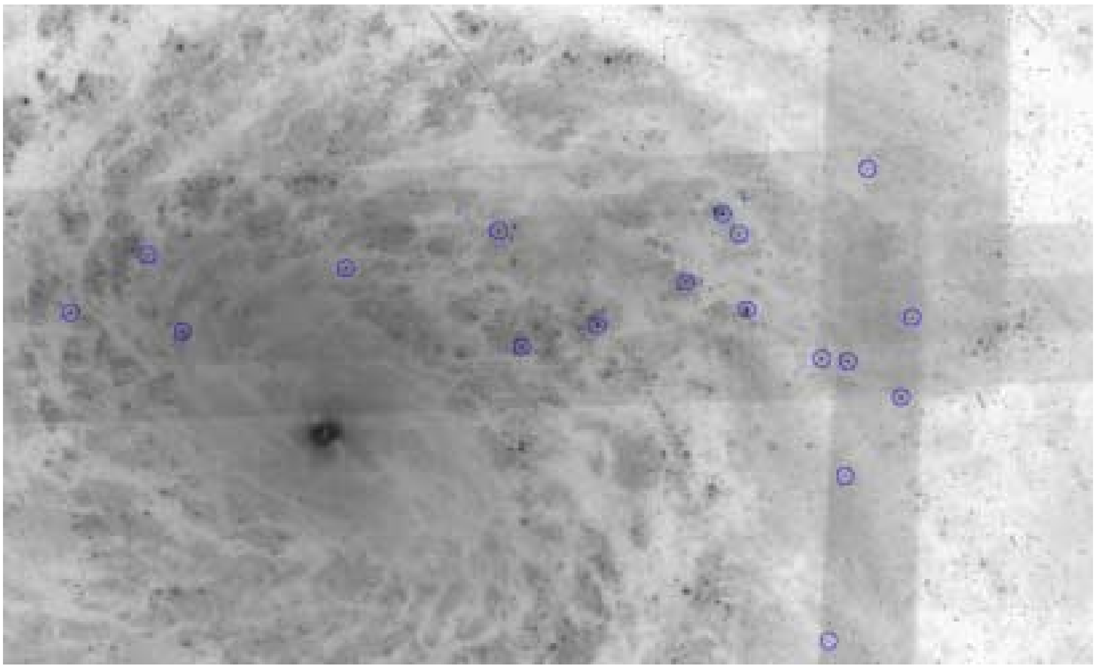
The mosaic has six primary pointing positions or tiles. Each of the six tiles has four individual frames. We arbitrarily define frame `j97c31rsq` (or simply "frame 31") in tile 3 to be the origin of the reference frame (0,0,0).

"Intertile" shifts and rotations are the (larger) shifts between the six tiles. These shifts can be on the order of ˜10 pixels, since different guide star pairs (or sometimes a single guide star) were used. These shifts were measured using only the first frames in each tile (frames 11,21,31,41,51,61). For example, the primary I-band frames used for registration are:

```
j97c11kdq_flt.fits
j97c21h4q_flt.fits
j97c31ruq_flt.fits
j97c41xmq_flt.fits
j97c51r6q_flt.fits
j97c61hcq_flt.fits
```

To measure the intertile shifts and rotations, the single-drizzled (distortion corrected `*single_sci.fits`) versions of these images were generated with `MultiDrizzle`, in the full undistorted mosaic output space. We set `clean=no` (to save the `*single_sci.fits` files), and avoid altering the input `flt` images by setting `skysub=no` (don't subtract sky), and `crbit=0` (don't update their data quality arrays).

Suitable registration objects (preferably stars, but sometimes clusters with a sharp peak) were visually identified: they must appear in multiple frames, be free of obvious cosmic ray contamination, and not be saturated and bleeding.



(c) Closeup showing stars used to measure intertile shifts and rotations, to register adjacent tiles in the mosaic

With `imexam`, we measured the x,y positions of 10-20 objects in the overlap regions of reference frame 31 (Figure c), and their positions in any overalpping frames. Frames 11,41,51 have long overlaps with frame 31, so objects were chosen which span the full length of each overlap. Frames 21 and 61 have very small overlaps with the reference frame 31, so their shifts were measured iteratively, i.e. after the corrective shifts and rotations had been applied to frames 11,41,51, so their (much larger) overlaps with frames 21,61 could also be used.

The shifts and rotations were solved for using the `geomap` task. The corrections for the six primary intertile frames were also applied to the other three frames in their respective tiles, thereby internally registering the entire mosaic within an rms of < 0.4 pixels (relative to frame 31, not registered to any astrometric standard). The shifts and rotations were assembled into a `shiftfile`, to be provided as input to `MultiDrizzle`.

Since our 2-point sub-pixel dither pattern does not sample optimally in both x and y directions, and to avoid creating prohibitively large output mosaics, we decided to retain the input pixel scale, rather than drizzle to a finer scale. Therefore, in these version 1.0 mosaics, only the larger intertile shifts and rotations were applied (any intratile corrections are negligible at this scale – typically no more than 0.2 pixels). With additional intratile registration, and with drizzling to a finer output scale, it may be possible to extract more spatial information from this data.

3. Rejection of cosmic rays and other artifacts

Only two of our 96 total frames exhibited non-standard artifacts (outside those described in section 2), requiring special attention. Both of the problematic frames were in the Hα (F658N) dataset. A significantly elevated background level in frame `j97c43n7q` (in tile 4) could not be explained by any improper bias level subtraction, or any violation (or approaching) of the Sun, Moon, or Earth limb avoidance angles, so this frame was excluded from the version 1.0 combination. This leads to a uneven weight map for H-alpha, and also leaves a small amount of cosmic ray contamination where the interchip gaps overlap in tile 4.

A broad and diffuse satellite trail is evident on chip 2 of frame `j97c64roq` (in tile 6). After measuring the endpoints and width of the satellite trail in the undistorted `*single_sci.fits` images, the `satmask` task (Richard Hook, internal communication) was used to generate a mask for the trail. This undistorted mask was then transformed (using `blot`) into the input distorted space of the `flt` images, assigned a unique flag value of 16384, and summed with the existing chip 2 data quality array: `j97c64roq_flt.fits[DQ,1]`

Although the rejection of cosmic rays and other undesireable artifacts is embedded in the `MultiDrizzle` processing descibed below, the following is an overview of how it is accomplished. A median image is constructed from the registered and undistorted single-drizzled (`*single_sci.fits`) images. This median image – or the appropriate sections of it – are blotted back to the distorted space of the input `flt` images, where it can be used to identify cosmic rays. The `dither` package tasks of `deriv` and `driz_cr` are used to compare this blotted image and its derivative image with the original input `flt` file, and generate a cosmic ray mask. Finally, all the `flt`, together with their newly created cosmic ray masks, are drizzled onto a single output mosaic, which has units of electrons/second in each pixel.

4. Image combination

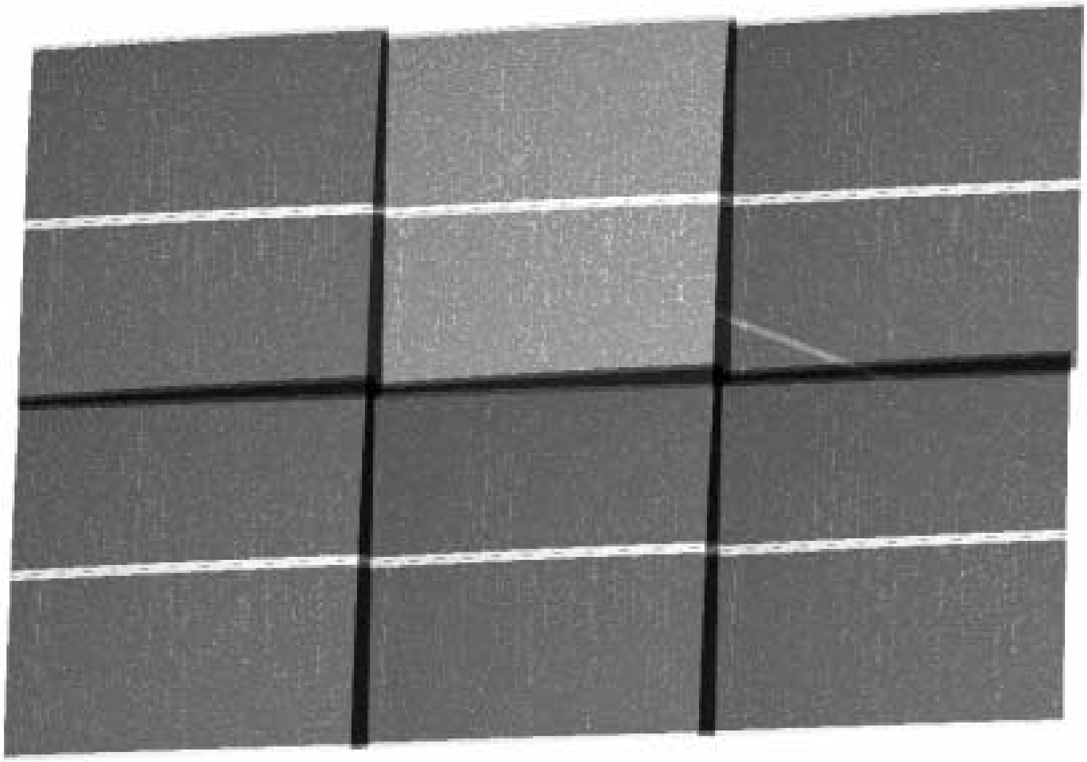
The IRAF/STSDAS `MultiDrizzle` task (Koekemoer et al., 2002) was used to combine the mosaics for each filter. `MultiDrizzle` is a PyRAF script which performs, on a list of input `flt` images: bad pixel identification, sky subtraction, rejection of cosmic rays and other artifacts (as described above), and a final drizzle combination with the cosmic ray masks, into a clean image. `MultiDrizzle` also applies the latest filter-specific geometric distortion corrections to each image, as specified in the IDCTAB reference tables. These mosaics were processed in the same environment as the HST pipeline (SunFire/smalls), with the following software versions: `PyFITS 0.9.6` (November 24, 2004), `numarray 1.2.3`, and `MultiDrizzle 2.5.6` (25 March 2005).

There are many `MultiDrizzle` parameters which can be adjusted. The pipeline uses carefully pre-defined sets of parameters (defined in the MDRIZTAB), but in the standalone environment, optimal combination parameters for a specific dataset can be found through some trial-and-error iterations. In Table 2, we list our key parameter settings, and here we explain some of our non-default parameter choices.

Since the galaxy fills most of the mosaic, sky subtraction was turned off (`skysub=no`). To prevent altering the input `flt` data quality arrays with the flags from `MultiDrizzle` rejections (flag 4096), we set `crbit=0` (note that the masks and weight maps still record the cosmic rays and artifacts rejected by `MultiDrizzle`). The cosmic ray rejection thresholds (`driz_cr_snr`) were raised a bit to avoid rejecting the cores of bright objects. The central RA,DEC and output image dimensions were fixed, and the orientation was set to rotate north up, and east to the left. Since these mosaics are so large (~420 MB each), we did not build them into multi-extension FITS files (`build=no`), i.e. the science array and weight maps are separate files. Wet set `bits=96` to retain the warm pixels and CTE tails of hot pixels (flags 64+32=96), which are flagged in the dark reference image.

Although the lanczos3 drizzle kernel produces drizzled output images with the least amount of correlated noise, it also performs poorly in the presence of even a small amount of cosmic ray contamination, or other artifacts with sharp edges (it produces a halo of negative pixels around them). We used the gaussian kernel which is a bit better at suppressing this correlated noise than the default square kernel, but correlated noise is still evident as a faint Moire-like pattern in the weight maps (see Figure d), which is also visible in the science data – especially in low signal-to-noise areas. For an excellent discussion of drizzle kernels, see Mei et. al, 2004.

The cosmic ray masks generated by `MultiDrizzle` are used as input to the final drizzle combination of all the images. The `drizzle` task (Fruchter and Hook, 2002) performs a weighted sum of the input images, and allows input pixels to be shrunk before being mapped onto the output plane (we set `pixfrac=0.9`). The output pixel scale (`final_scale`) can also be different than the input (detector) pixel scale – a smaller pixel scale can allow more spatial information to be recovered if the data are well-dithered – but we opted to retain the input WFC scale of 0.05 arcsec per pixel.



(d) H-alpha (F658N) exposure weight map

`MultiDrizzle` also produces exposure weight maps, which indicate the background and instrumental noise for each pixel in the science data. The total exposure time varies significantly from pixel-to-pixel across the final mosaic, mainly due to overlaps between adjacent tiles, interchip gaps, and all the bad pixels which are rejected. The weight maps were visually inspected to ensure that rejected artifacts have appropriately lower weight – and equally importantly, that real objects (e.g. the cores of stars, or of the core of M51) are not being rejected. The only irregular rejection was related to long diffraction spikes and/or bleeding (from saturation) around bright foreground stars (which is to be expected). Figure d shows the Hα weight map, with the lower-weighted pixels brightest (e.g. interchip gaps, the masked satellite trail, cosmic rays, detector artifacts, and tile 4 with only three `flt` frames used), and the higher-weighted pixels darkest (e.g. uncontaminated pixels and tile overlaps).

The photometric fidelity of the `MultiDrizzle` code is reliable to a high degree of accuracy, since the underlying algorithm for drizzle is designed to be flux-conserving (see Fruchter & Hook, 2002, and Koekemoer et al., 2002). The MultiDrizzle team has verified this in practice by using a suite of test datasets to compare photometry from different exposures of the same objects, and verifying that these provide good agreement to better than the ACS flatfield/photometric calibration accuracy (1-2%) for bright sources, and Poisson noise for fainter sources. But these M51 version 1.0 mosaics were not directly tested for photometric accuracy, nor for PSF stability across the field.

Table 2: The key set of MultiDrizzle parameters used for the final mosaic combination

MultiDrizzle parameter	value	note
input =	@list_flt_all	Input files (list of flt images)
output =	h_m51_i_s05	Rootname for output
context =	no	Make context image?
clean =	yes	Remove temporary files?
ra =	202.4675	Central RA of output mosaic
dec =	47.2138	Central DEC of output mosaic
build =	no	Multi-extension output file?
shiftfile =	shifts_geomap	Shifts and rotations to be applied
STEP 1: static =	yes	Create static bad pixel mask?
static_sig =	4.0	rms clipping for static mask
STEP 2: skysub =	no	Subtract sky background?
STEP 3: driz_separate =	yes	Make separate drizzled images?
driz_sep_outnx =	8600	Nice round x-dimension
driz_sep_outny =	12200	Nice round y-dimension
driz_sep_kernel =	turbo	Fast drizzle drop shape here
driz_sep_scale =	INDEF	Use the input pixel scale
driz_sep_pixfrac =	1.0	Drizzle drop size
driz_sep_rot =	0.0	Rotate north up, east left
driz_sep_bits =	96	Includes warm and CTE pixels
STEP 4: median =	yes	Create a median image?
STEP 5: blot =	yes	Blot median to input frame?
STEP 6: driz_cr =	yes	Reject cosmic-rays and artifacts?
driz_cr_snr =	5.0 4.0	CR S/N detection thresholds
driz_cr_scale =	1.2 0.7	CR scale parameter
STEP 7: driz_combine =	yes	Perform final drizzle combination?
final_wht_typ =	EXP	Weighting for final drizzle
final_outnx =	8600	Nice round output x-dimension
final_outny =	12200	Nice round output y-dimension
final_kernel =	gaussian	Drizzle drop shape
final_wt_scl =	exptime	Weighting factor for input image
final_scale =	0.05	Output pixel scale in arcsec
final_pixfrac =	0.9	Drizzle drop size in input pixels
final_rot =	0.0	This rotates north up, east left
final_fillval =	INDEF	Value for undefined output pixels
final_bits =	96	Includes warm and CTE pixels
crbit=	0	Don't add DQ flags (4096) to flt images

5. Files and filenaming convention

The following files are our drizzled science data (`*_drz_sci.fits`) with corresponding weight maps (`*_weight.fits`), in FITS format. These have a scale of 0.05 arcsec per pixel ("s05"), and have dimensions of 8600 x 12200 pixels (~420 MB each). One each for B-band (F435W filter or "b") V-band (F555W filter or "v"), H-alpha narrow-band (F658N filter or "h"), and I-band (F814W filter or "i"):

```
h_m51_b_s05_drz_sci.fits
h_m51_v_s05_drz_sci.fits
h_m51_h_s05_drz_sci.fits
h_m51_i_s05_drz_sci.fits
h_m51_b_s05_drz_weight.fits
h_m51_v_s05_drz_weight.fits
h_m51_h_s05_drz_weight.fits
h_m51_i_s05_drz_weight.fits
```

Low-resolution (1/4) block-averaged FITS versions of each mosaic and weight map were also produced using the IRAF `blkavg` task, mainly for "quick-look" downloading and viewing, or for educational purposes (not intended for scientific analysis). These have a scale of 0.20 arcsec per pixel ("s20"), and dimensions of 2150 x 3050 pixels (~26 MB each, or 1/16 the size of the full-resolution mosaics above).

```
h_m51_b_s20_drz_sci.fits
h_m51_v_s20_drz_sci.fits
h_m51_h_s20_drz_sci.fits
h_m51_i_s20_drz_sci.fits
h_m51_b_s20_drz_weight.fits
h_m51_v_s20_drz_weight.fits
h_m51_h_s20_drz_weight.fits
h_m51_i_s20_drz_weight.fits
```

Much smaller preview GIF images of all of the above are also available on the MAST website. The resulting color composite images are available from the associated press release:
http://hubblesite.org/newscenter/newsdesk/archive/releases/2005/12/image/a

6. Acknowledgements

Thanks to STScI Director Steve Beckwith for granting 24 orbits of Director's Discretionary observing time to the Hubble Heritage Team to conduct this program. Thanks also to Warren Hack, Chris Hanley, Richard Hook, Marco Sirianni, John Blakeslee, Anton Koekemoer, Inga Kamp, Karen Levay, Faith Abney, and Randy Thompson for their contributions to this project.

If you utilize these mosaics for scientific analysis, please acknowledge and/or reference this paper (Mutchler et al., 2005, *AAS*, Vol.37, No.2). Although the AAS publishes only the abstracts of poster papers, our Abstract provides the MAST M51 website URL, where the full text of this paper can be downloaded, along with our FITS mosaics:
http://archive.stsci.edu/prepds/m51/

7. References

Fruchter & Hook, 2002, PASP 114, 144

Koekemoer, Fruchter, Hook, & Hack, 2002, HST Calibration Workshop, Ed. S. Arribas, A. M. Koekemoer, B. Whitmore (STScI: Baltimore), p.337

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Mei, Blakeslee, Tonry, Jordan, Peng, Cote', Ferrarese, Merritt, Milosavljevic, & West, 2005, "The ACS Virgo Cluster Survey. IV. Data Reduction Procedures for Surface Brightness Fluctuation Measurements with the Advanced Camera for Surveys", ApJS, 156:113-125