

Globular Clusters and Low-Mass X-Ray Binaries in M87

Daniel-Jens Kusterer, Amelia Bayo,
Sinan Alis, Genoveva Micheva
Tutor: Andrés Jordán

ESO NEON Summer School

NEON 2006 - 08.09.2006

Outline

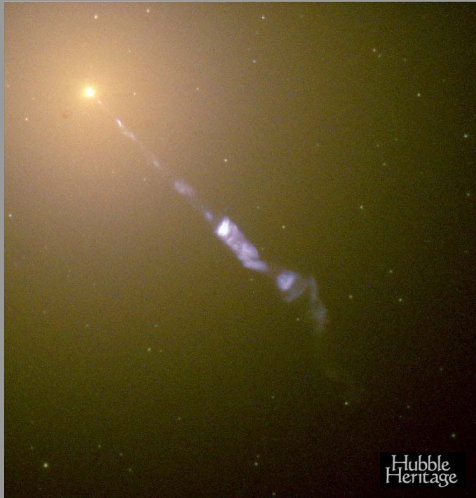
- 1 Introduction
 - Motivation
 - Globular Clusters
 - Low-Mass X-Ray Binaries
 - Instrument introduction
- 2 Data Analysis
 - HST Data
 - Chandra Data
- 3 Results and Conclusions
 - Discussion
 - Results

Motivation



- In Milky Way globular clusters form LMXBs efficiently
 - Small sample!
 - Look at M87
 - M87 richest globular cluster system in local universe
 - Increased GC sample of ~ 14000
 - Study properties of GCs hosting LMXBs

Motivation



- In Milky Way globular clusters form LMXBs efficiently
 - Small sample!
 - Look at M87
- M87 richest globular cluster system in local universe
 - Increased GC sample of ~ 14000
 - Study properties of GCs hosting LMXBs

Globular Clusters



- Spherical collection of stars orbiting a galaxy
 - Small and dense
 - Dust and gas free
 - Diameter independent of mass
- Old systems, mainly population II stars
- Luminosity Function used as standard candle

Globular Clusters



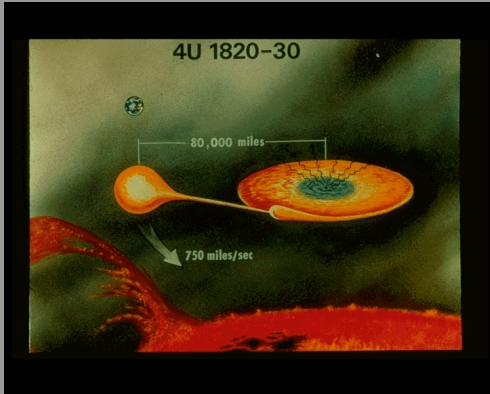
- Spherical collection of stars orbiting a galaxy
 - Small and dense
 - Dust and gas free
 - Diameter independent of mass
- Old systems, mainly population II stars
- Luminosity Function used as standard candle

Globular Clusters



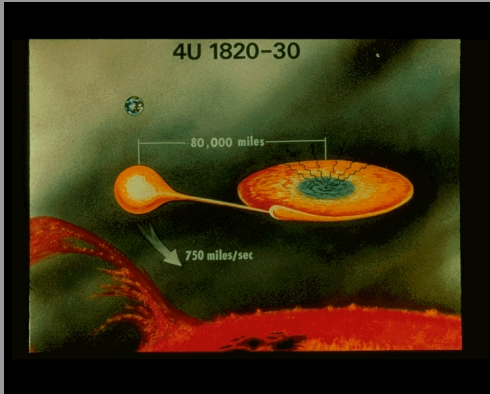
- Spherical collection of stars orbiting a galaxy
 - Small and dense
 - Dust and gas free
 - Diameter independent of mass
- Old systems, mainly population II stars
- Luminosity Function used as standard candle

Low-Mass X-Ray Binaries



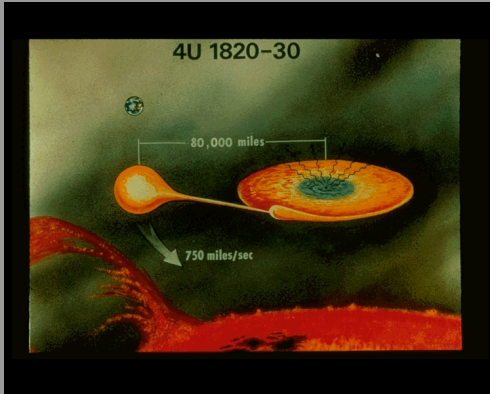
- Binary Systems
 - Neutron star or blackhole primary
 - Late-type secondary
 $M \lesssim 2.0M_{\odot}$
- Mass overflow (Roche lobe filling)
- $L \sim 10^{35} - 10^{39}$ erg/s
- Older than 10^9 yr
- Possible formation
 - Direct formation
 - Tidal capture
 - Binary exchange processes

Low-Mass X-Ray Binaries



- Binary Systems
 - Neutron star or blackhole primary
 - Late-type secondary
 $M \lesssim 2.0M_{\odot}$
- Mass overflow (Roche lobe filling)
- $L \sim 10^{35} - 10^{39}$ erg/s
- Older than 10^9 yr
- Possible formation
 - Direct formation
 - Tidal capture
 - Binary exchange processes

Low-Mass X-Ray Binaries



- Binary Systems
 - Neutron star or blackhole primary
 - Late-type secondary
 $M \lesssim 2.0M_{\odot}$
- Mass overflow (Roche lobe filling)
- $L \sim 10^{35} - 10^{39}$ erg/s
- Older than 10^9 yr
- Possible formation
 - Direct formation
 - Tidal capture
 - Binary exchange processes

Optical and X-Ray data



ACS Wide Field Camera
202" \times 202" FoV
2 \times 560s + 90s F850LP (\simeq z band)
2 \times 375s F475W (\simeq g band)



ACIS Imaging mode
8' \times 8' FoV (S3)
105 ks exposure time

Obtaining optical data

Archive Status **HST Search Form** [\(Help\)](#)

[Standard Form](#) [File Upload Form](#)

Target Name **Resolver** **Radius (arcmin)**

Right Ascension **Declination** **Equinox**

Imagers	Spectrographs	Other	Start Time	Exp Time	Proposal ID	Release Date
<input type="button" value="ALL"/> <input type="button" value="NONE"/>	<input type="button" value="ALL"/> <input type="button" value="NONE"/>	<input type="button" value="ALL"/> <input type="button" value="NONE"/>	<input type="text"/>	<input type="text"/>	9401	<input type="text"/>
<input type="checkbox"/> STIS <input type="checkbox"/> NICMOS <input type="checkbox"/> WFPC2	<input type="checkbox"/> STIS <input type="checkbox"/> NICMOS <input type="checkbox"/> GHRS	<input type="checkbox"/> FGS <input type="checkbox"/> HSP	Dataset <input type="text"/>	Filters/Gratings <input type="text"/>	Obset ID <input type="text"/>	Archive Date <input type="text"/>
			Target Descrip	Apertures	Observations	

Obtaining optical data

Archive Status **HST Search Form** ([Help](#))

[Standard Form](#) [File Upload Form](#)

Target Name **Resolver** **Radius (arcmin)**
M87 SIMBAD 3.0

Right Ascension **Declination** **Equinox**
 12000

Imagers **Spectrographs** **Other** **Start Time** **Exp Time** **Proposal ID** **Release Date**
 9401

 Dataset **Filters/Gratings** **Obset ID** **Archive Date**
 STIS STIS FGS

NICMOS NICMOS HSP **Target Descrip** **Apertures** **Observations**
 WFPC2 GHRS WF/PC Science Calibration

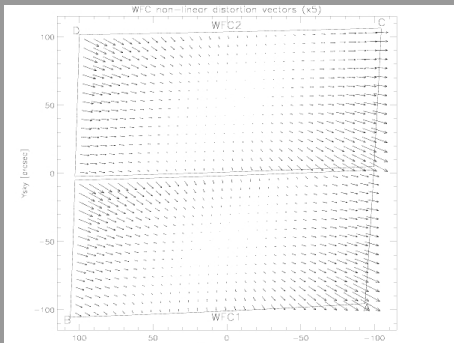
FOC FOC **PI Last Name**

ACS ACS **User-specified field 1** **Field Descriptions** **User-specified field 2** **Field Descriptions**
 Dataset Dataset

Output Columns **Sort By:**
 Mark and_sep (?) Reverse

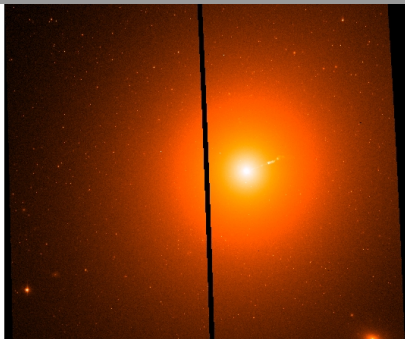
- Obtain data from <http://archive.stsci.edu/hst>
- Program ID: GO-9401
- Program PI: Patrick Côté

Processing optical data



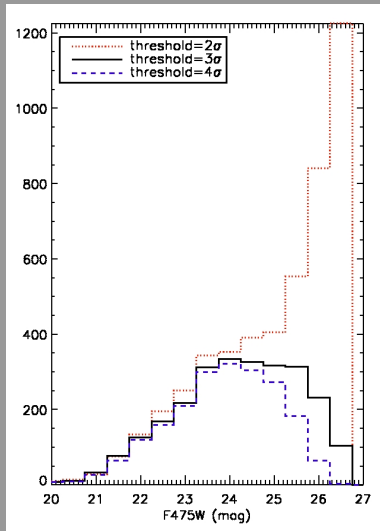
- Software: PyRAF
- Necessity of drizzling with *multidrizzle* (calibration files)
 - corrects for built-in geometric distortion (off-axis location of instrument)
 - restores information lost due to undersampling
 - combines dithered images
 - filters cosmic rays

Processing optical data



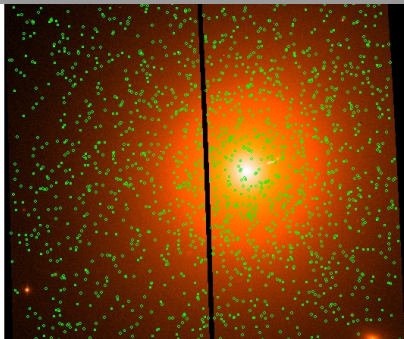
- Software: SExtractor
- Source extracting in both bands
 - DETECT_MINAREA 5
 - DETECT_THRESH 3
 - PHOT_APERTURES 4 8 10 16
 - SATUR_LEVEL 65000
 - MAG_ZEROPOINT 26.068 (F475W, AB)
 - MAG_ZEROPOINT 24.862 (F850LP, AB)
 - PIXEL_SCALE 0.049
 - SEEING_FWHM 0.098
 - BACK_SIZE 32

Processing optical data



- Software: SExtractor
- Source extracting in both bands
 - DETECT_MINAREA 5
 - DETECT_THRESH 3
 - PHOT_APERTURES 4 8 10 16
 - SATUR_LEVEL 65000
 - MAG_ZEROPOINT 26.068 (F475W, AB)
 - MAG_ZEROPOINT 24.862 (F850LP, AB)
 - PIXEL_SCALE 0.049
 - SEEING_FWHM 0.098
 - BACK_SIZE 32

Processing optical data



- 2608 sources (F475W)
- 2372 sources (F850LP)
- 1911 sources (cross-matched) with TOPCAT

Processing optical data

Match Tables

File Help

Match Criteria

Algorithm: Sky

Max Error: 0.1 arcsec

Table 1

Table: 1: F475W

RA column: RA degrees

Dec column: DEC degrees

Table 2

Table: 2: F850LP

RA column: RA degrees

Dec column: DEC degrees

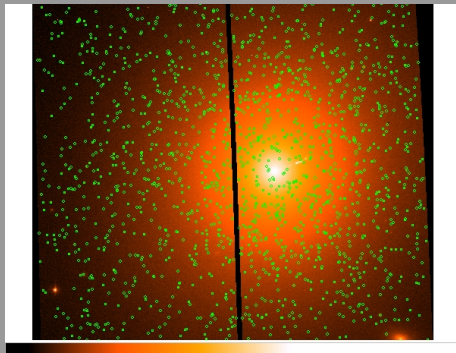
Output Rows

Match Selection: Best Match Only All Matches

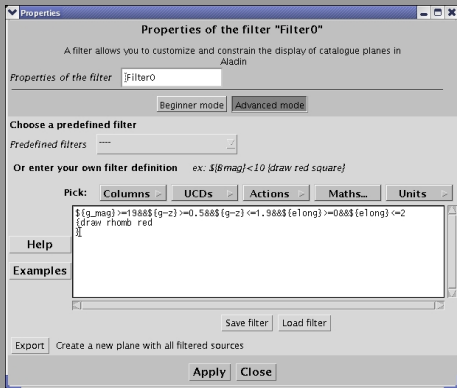
Join Type: 1 and 2

Go Stop

- 2608 sources (F475W)
- 2372 sources (F850LP)
- 1911 sources (cross-matched) with TOPCAT

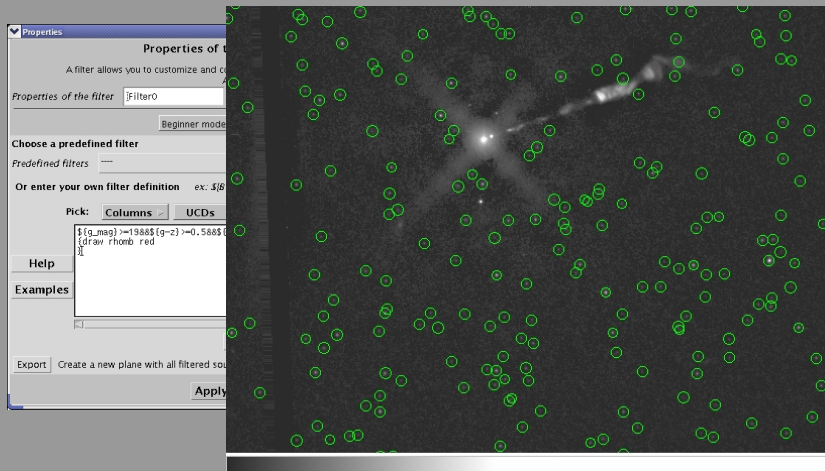


Filtering optical data



- Aladin filter applied to cross-matched catalog
 - $0.5 \leq g-z \leq 1.9$
 - $m_z > 19$
 - $m_g > 19$
 - $0 < \text{elongation} < 2$

Filtering optical data

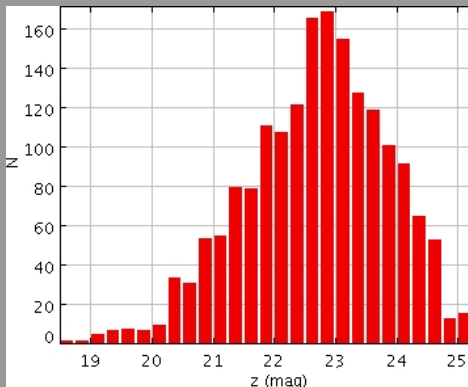


The image displays a software interface for filtering astronomical data. On the left, a 'Properties' window titled 'Properties of t' is visible. It contains a text field for the filter name, currently set to 'Filter0'. Below this, there are sections for 'Choose a predefined filter' and 'Or enter your own filter definition'. The latter section includes a 'Pick:' dropdown menu with 'Columns' and 'UCDs' options, and a text area containing the filter definition: `$(g_mag) >= 19.68 && (g-z) >= 0.588 && {draw rhomb red}`. There are also 'Help', 'Examples', and 'Export' buttons. The 'Export' button is labeled 'Create a new plane with all filtered sou'. An 'Apply' button is located at the bottom right of the window. On the right, an astronomical image shows a galaxy with a bright central region and a diffuse, elongated structure. Numerous green circles are overlaid on the image, representing the objects that have been filtered according to the specified criteria.

Analyzing optical data

- Calculate distance
 - $m_z - M_z = 5 \log d - 5 + A_z$
 - $E(B - V) = 0.022$ (taken from NED database)
 - $A_z = 1.485 \times E(B - V)$ (from Jordán et al., 2004)
 - $m_{peak} \simeq 22.8$ (for the z band)
 - $(M_{peak}/L_{peak})_z \sim 1.5 \times (M_{\odot}/L_{\odot})$ (from PÉGASE models)
 - $M_{peak} - M_{\odot} = 2.5 \log(L_{\odot}/L_{peak})$

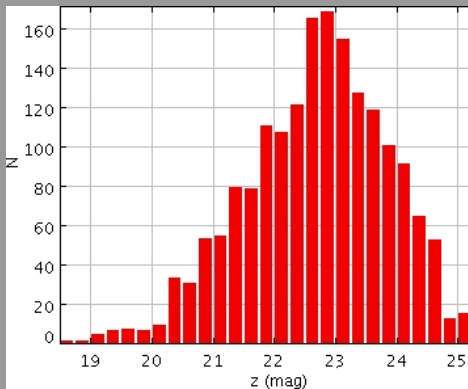
Where m , M , A_z are apparent and absolute magnitudes and extinction, resp.



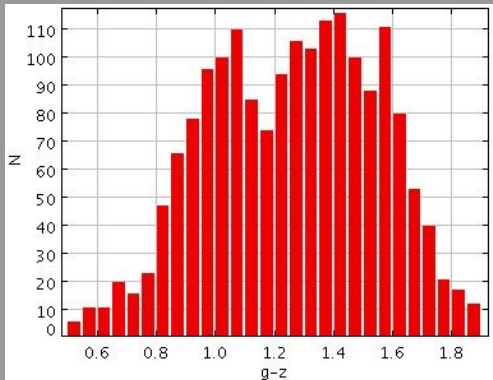
Analyzing optical data

- Calculate distance

16.1 Mpc

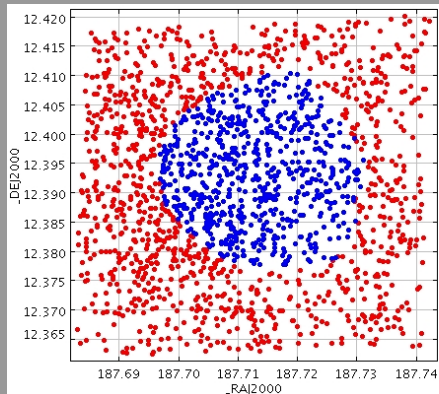


Analyzing optical data



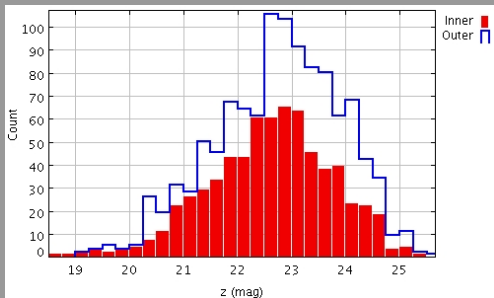
- Two distinct populations
 - $g - z < 1.2$
 - $g - z > 1.2$
- Two different mean metallicities

Analyzing optical data



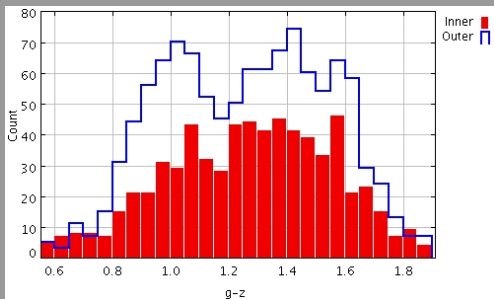
- Comparison between inner and outer part of the population
 - Define two regions
 - No significant shift of the peaks
 - BUT: More metal-rich in inner part

Analyzing optical data



- Comparison between inner and outer part of the population
 - Define two regions
 - No significant shift of the peaks
 - BUT: More metal-rich in inner part

Analyzing optical data



- Comparison between inner and outer part of the population
 - Define two regions
 - No significant shift of the peaks
 - BUT: More metal-rich in inner part

Obtaining X-ray data



Observation Search

[New Search](#)

[Retrieval List](#) [Help](#)



Search

Target Name	<input type="text" value="M87"/>	Resolve Name	<input type="text"/>	RA/Long/l	<input type="text" value="12 30 49.42"/>	Dec/Lat/b	<input type="text" value="+12 23 28.04"/>	Radius	<input type="text" value="10"/>	arcmin
Name Resolver	<input type="text" value="SIMBAD/NED"/>	Coordinate System	<input type="text" value="Equatorial J2000"/>	Equinox	<input type="text" value="2000"/>					
Observation ID	<input type="text" value="2707"/>	Sequence Number	<input type="text"/>	Proposal Number	<input type="text" value="03400562"/>					
Proposal Title	<input type="text"/>	PI Name	<input type="text"/>	Observer Name	<input type="text"/>					
Start Date	<input type="text"/>	Public Release Date	<input type="text"/>	Exposure Time (ks)	<input type="text"/>					

Status	<input type="text" value="Archived"/>	Science Category	<input type="text" value="Solar System"/>	Joint Observatories	<input type="text" value="None"/>
	<input type="text" value="Observed"/>		<input type="text" value="Stars and WD"/>		<input type="text" value="HST"/>
	<input type="text" value="Partially Observed"/>		<input type="text" value="WD Binaries and CV"/>		<input type="text" value="NOAO"/>
	<input type="text" value="Scheduled"/>		<input type="text" value="BH and NS Binaries"/>		<input type="text" value="RXTE"/>
	<input type="text" value="Unobserved"/>		<input type="text" value="SN, SNR and Isolated NS"/>		<input type="text" value="Spitzer"/>
Instrument	<input type="text" value="ACIS-I"/>	Grating	<input type="text" value="None"/>	Type	<input type="text" value="TOO"/>
	<input type="text" value="ACIS-S"/>		<input type="text" value="LETG"/>		<input type="text" value="CAL"/>
	<input type="text" value="HRC-I"/>		<input type="text" value="HETG"/>		<input type="text" value="GO"/>
	<input type="text" value="HRC-S"/>				<input type="text" value="GTO"/>
					<input type="text" value="DDT"/>
					<input type="text" value="A00"/>
					<input type="text" value="A01"/>
					<input type="text" value="A02"/>
					<input type="text" value="A03"/>
					<input type="text" value="A04"/>

Customize Output:

Sort Order: ascending descending

Display: Format Row Limit

Coordinate System: Equinox Format

For online support please contact the [CXC Helpdesk](#).

Obtaining X-ray data

Chandra X-ray Center Chandra Data Archive

Observation Search

Search Retrieval List Help

Target Name: M87 Resolve Name RA(Long): 12 30 49.42 Dec(Lat): -12 23 28.04 Radius: 10 arcmin

Name Resolver: SIMBAD/NED Coordinate System: Equatorial J2000 Equinox: 2000

Observation ID: 2707 Sequence Number: Proposal Number: 03400562

Disposal Title: PI Name: Observer Name:

Start Date: Public Release Date: Exposure Time (ks):

Status: Archived Observed Partially Observed Scheduled Unobserved

Science Category: Solar System Stars and WD WD Binaries and CV BH and NS Binaries SN, SNR and Isolated NS

Instrument: ACIS-I ACIS-S HRC-I HRC-S

Filtering: None LETG HETG

Type: TOO CAL GO GTO DDT

Observing Cycle: A00 A01 A02 A03 A04

Joint Observatories: None HST NOAO RXTE Spitzer

Customize Output:

Sort Order: Status ascending descending

Display: External HTML Row Limit: 50

Coordinate System: Equatorial J2000 Equinox: 2000 Format: Sexagesimal (hh:mm:ss.ss)

For online support please contact the [CXU Helpdesk](#).

- Obtain data from <http://cda.harvard.edu/chaser/dispatchOcat.do>
- Obs ID: 2707
- Program PI: Patrick Côté

Processing X-ray data

Index	Extension	Type	Dimension	View
<input type="checkbox"/> 0	Primary	Image	0	Header Image Table
<input type="checkbox"/> 1	EVENTS	Binary	18 cols X 6455032 rows	Header Hist Plot All Select
<input type="checkbox"/> 2	GTI	Binary	2 cols X 11 rows	Header Hist Plot All Select
<input type="checkbox"/> 3	GTI	Binary	2 cols X 3 rows	Header Hist Plot All Select
<input type="checkbox"/> 4	GTI	Binary	2 cols X 1 rows	Header Hist Plot All Select
<input type="checkbox"/> 5	GTI	Binary	2 cols X 3 rows	Header Hist Plot All Select
<input type="checkbox"/> 6	GTI	Binary	2 cols X 4 rows	Header Hist Plot All Select
<input type="checkbox"/> 7	GTI	Binary	2 cols X 2 rows	Header Hist Plot All Select

- One event per photon
 - Photon energy, position & time of arrival stored
- Possibility of obtaining spectra and images

Processing X-ray data

File Edit Tools Help

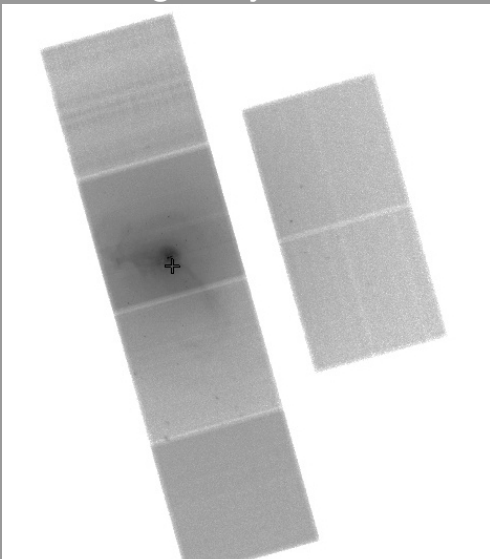
Select All Invert

	time 1D s	ccd_id 11	node_id 11	expno 1J	chipx 11 pixel	chipy 11 pixel	tdetx 11 pixel	tdety 11 pixel	detx 1E pixel	dety 1E pixel	x 1E pixel	y 1E pixel
1	1.423799869622E+08	2	0	3	54	63	3124	4032	3.089413E+03	2.285412E+03	6.096516E+03	3.619580E+03
2	1.423799869622E+08	2	3	3	824	84	3145	3262	3.112983E+03	3.053402E+03	5.350648E+03	3.435065E+03
3	1.423799869622E+08	2	3	3	882	280	3341	3204	3.308089E+03	3.111021E+03	5.242524E+03	3.607390E+03
4	1.423799869622E+08	2	0	3	51	388	3449	4035	3.414205E+03	2.282513E+03	6.011675E+03	3.933110E+03
5	1.423799869622E+08	2	3	3	887	431	3492	3199	3.459158E+03	3.116515E+03	5.196474E+03	3.751373E+03
6	1.423799869622E+08	2	1	3	400	542	3603	3686	3.568831E+03	2.630400E+03	5.634971E+03	3.988138E+03
7	1.423799869622E+08	2	3	3	799	623	3684	3287	3.650570E+03	3.028932E+03	5.229164E+03	3.959317E+03
8	1.423799869622E+08	2	1	3	327	727	3788	3759	3.752404E+03	2.558263E+03	5.654902E+03	4.184366E+03
9	1.423799869622E+08	2	1	3	377	952	4013	3709	3.977418E+03	2.607432E+03	5.546846E+03	4.387768E+03
10	1.423799870032E+08	7	3	3	881	10	4798	1712	4.761073E+03	4.602163E+03	3.414655E+03	4.604163E+03
11	1.423799870032E+08	7	2	3	671	12	4588	1714	4.551036E+03	4.600621E+03	3.472810E+03	4.402331E+03
12	1.423799870032E+08	7	0	3	74	18	3991	1720	3.955225E+03	4.595276E+03	3.638712E+03	3.830059E+03
13	1.423799870032E+08	7	2	3	686	22	4603	1724	4.566297E+03	4.590324E+03	3.478607E+03	4.419848E+03
14	1.423799870032E+08	7	0	3	85	28	4002	1730	3.966067E+03	4.585139E+03	3.645548E+03	3.843234E+03
15	1.423799870032E+08	7	2	3	665	44	4582	1746	4.545069E+03	4.568715E+03	3.505142E+03	4.405194E+03
16	1.423799870032E+08	7	0	3	248	47	4165	1749	4.128573E+03	4.566060E+03	3.620073E+03	4.004861E+03
17	1.423799870032E+08	7	0	3	24	52	3941	1754	3.905077E+03	4.561281E+03	3.684976E+03	3.790943E+03
18	1.423799870032E+08	7	0	3	118	55	4035	1757	3.998686E+03	4.557890E+03	3.662985E+03	3.881995E+03
19	1.423799870032E+08	7	0	3	206	61	4123	1763	4.087201E+03	4.551770E+03	3.644996E+03	3.968879E+03
20	1.423799870032E+08	7	0	3	176	71	4093	1773	4.056795E+03	4.541694E+03	3.662902E+03	3.942319E+03

Go to: Edit cell:

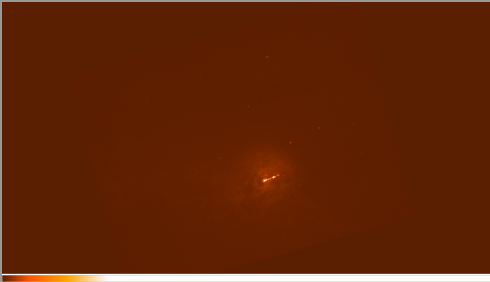
- One event per photon
 - Photon energy, position & time of arrival stored
- Possibility of obtaining spectra and images

Processing X-ray data



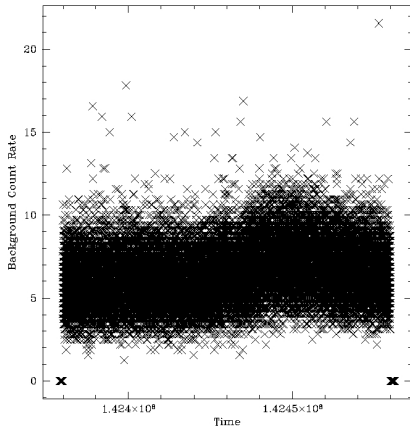
- 6 ACIS chips
- Using Software CIAO to:
 - Cut to S3
 - Restrict the image to HST FoV
 - Construct the background light curve (S1)
 - No background flares

Processing X-ray data



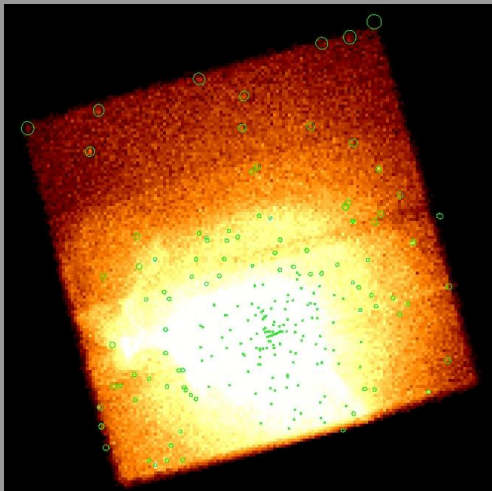
- 6 ACIS chips
- Using Software CIAO to:
 - Cut to S3
 - Restrict the image to HST FoV
 - Construct the background light curve (S1)
- No background flares

Processing X-ray data



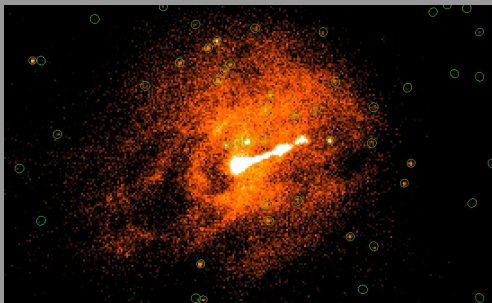
- 6 ACIS chips
- Using Software CIAO to:
 - Cut to S3
 - Restrict the image to HST FoV
 - Construct the background light curve (S1)
- No background flares

Processing X-ray data



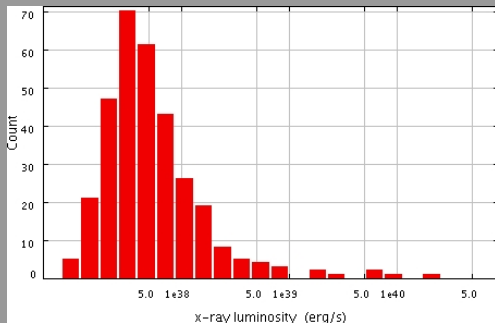
- *celldetect* source extraction algorithm (alt. *wavdetect*)
- Manual removal of problematic regions

Processing X-ray data



- *celldetect* source extraction algorithm (alt. *wavdetect*)
- Manual removal of problematic regions

Analyzing X-ray data



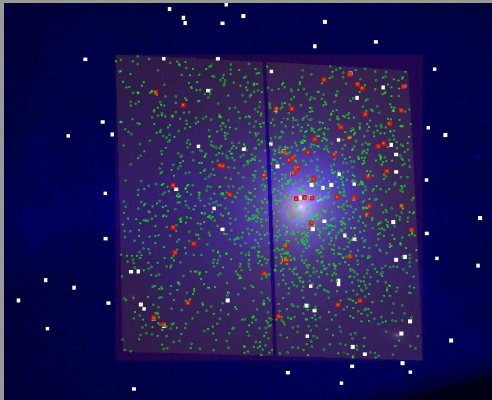
- LF shape compatible with LMXB population, peak artificial
- Higher luminosities suggest possible BH presence

Cross-matching optical & X-rays



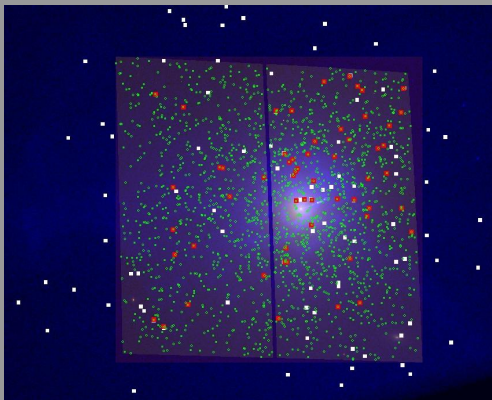
- RGB image (ds9)
 - Red: F850LP (\simeq Sloan z)
 - Green: F475W (\simeq Sloan g)
 - Blue: X-ray
- Cross-matching the catalogues
 - Green: Optical catalogue
 - White: X-ray catalogue
 - Red: Cross-matched

Cross-matching optical & X-rays



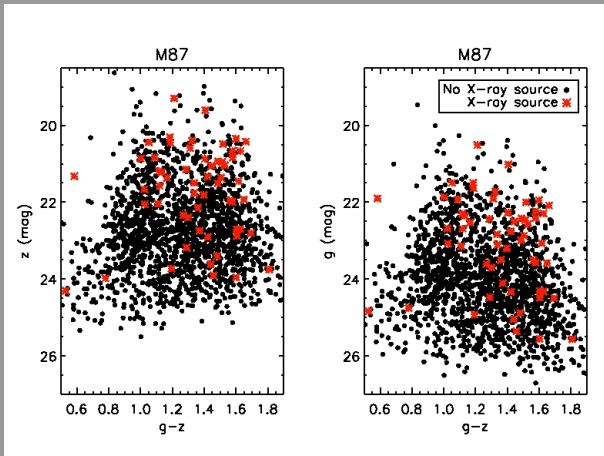
- RGB image (ds9)
 - Red: F850LP (\approx Sloan z')
 - Green: F475W (\approx Sloan g)
 - Blue: X-ray
- Cross-matching the catalogues
 - Green: Optical catalogue
 - White: X-ray catalogue
 - Red: Cross-matched

Cross-matching optical & X-rays



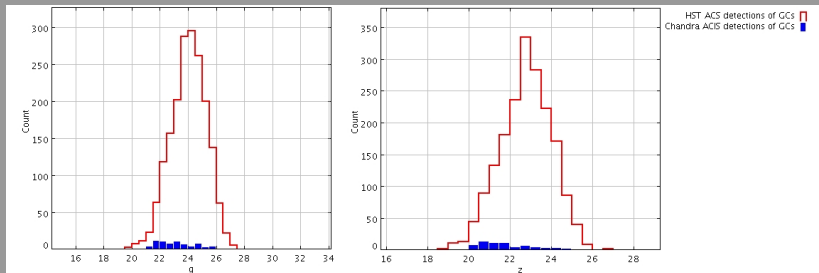
- Cross-match performed with TOPCAT
- Using RA & DEC for matching (0.1" threshold)
 - 1769 optical sources
 - 179 X-ray sources
 - 57 cross-matches

Properties of optical counterparts



- Redder in color
- Brighter in g & z mag
- ~ 2 times more frequent in the red peak

Properties of optical counterparts



- Different behaviour of two populations
 - GCs containing LMXBs are brighter
- Higher density favours LMXB formation

THANK YOU!