AstroSat/UVIT measurement of the structure and star formation history of the centre of M31

Denis Leahy,

Dept. of Physics and Astronomy

University of Calgary

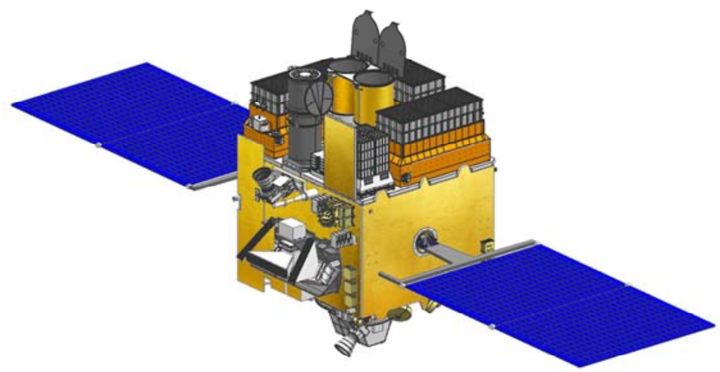
Contributions from students M. Buick, T. Craicu, C. Leahy, C. Morgan, N. Seminoff

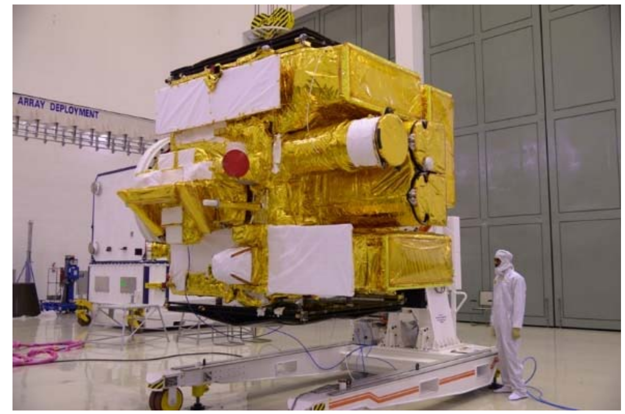
This work is supported by grants from the Canadian Space Agency and NSERC.

Overview

- AstroSat observatory and UVIT instrument
- M31 AstroSat/UVIT observations
- SED analysis and SFH of M31
- Structure analysis of M31
- Summary

AstroSat: Multiwavelength Space Observatory





The ASTROSAT collaboration:

Indian Space Research Organization,

Canadian Space Agency

Raman Research Institute, Bangalore

Inter-University Centre for Astronomy and Astrophysics, Pune

Tata Institute of Fundamental Research, Mumbai

Indian Institute of Astrophysics, Bangalore

Bhabha Atomic Research Centre, Mumbai

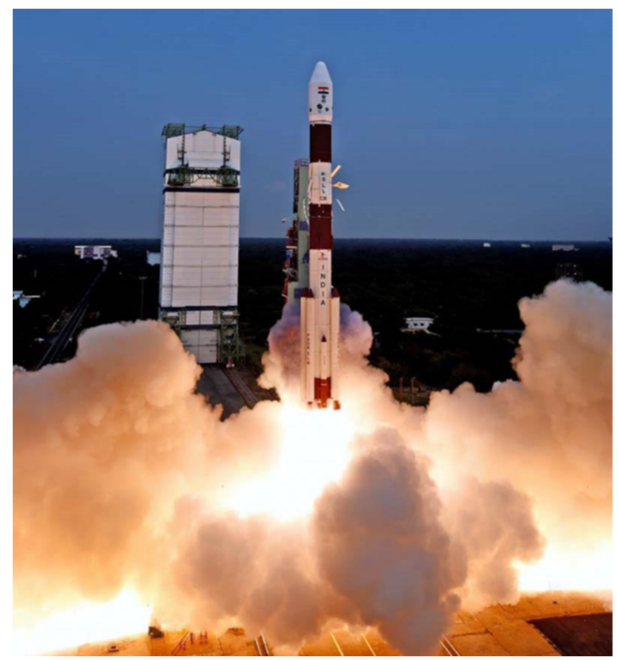
Presidency University, Kolkata

S.N. Bose National Centre for Basic Sciences, Kolkata

University of Leicester

Instruments:
X-ray: LAXPC, CZT, SXT, SSM
UV and VIS: UVIT

launched on 28th September 2015
by PSLVC30(XL) from Sriharikota



UVIT resolution 1”

Comparison of GALEX DS image (lower left), UVIT F148W image (lower center) and HST/PHAT f275w catalog (red squares, lower right)

UVIT can resolve a significant number of stars in M31.

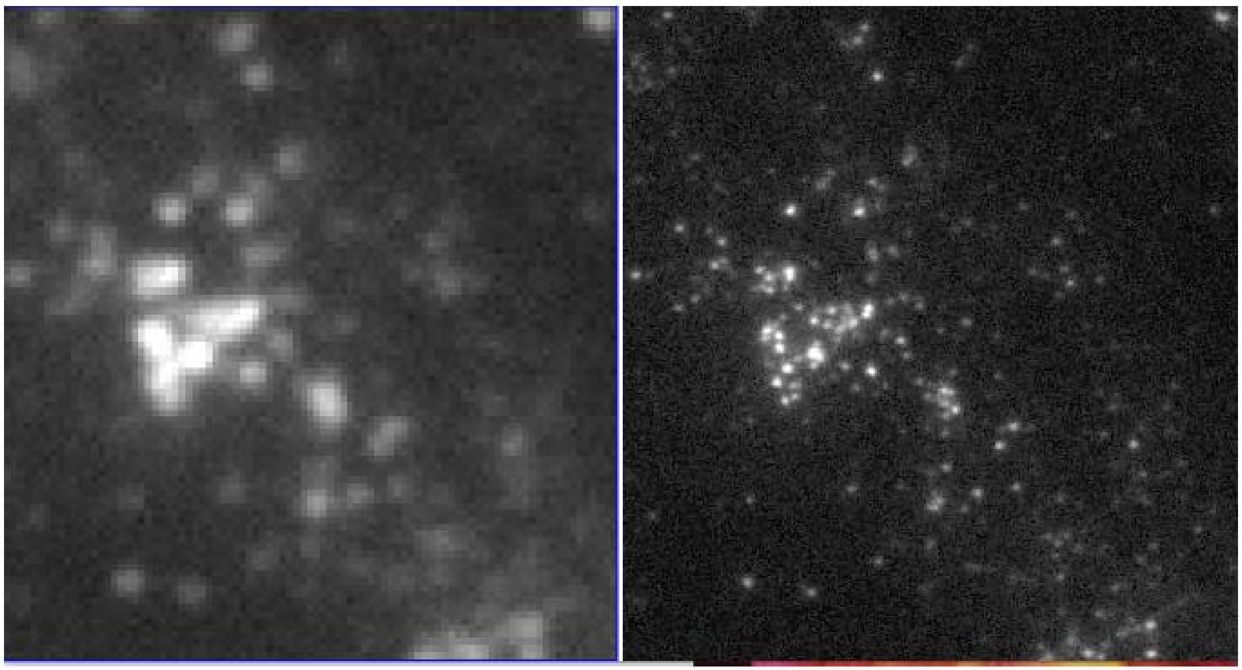


Figure 5. Comparison of the GALEX image (left) with the UVIT FUV CaF2 image (right) for the same region in M31. The area is 1.5 arcmin across and centered at R.A. 00:44:40.5 Dec.+41:26:37 (J2000).

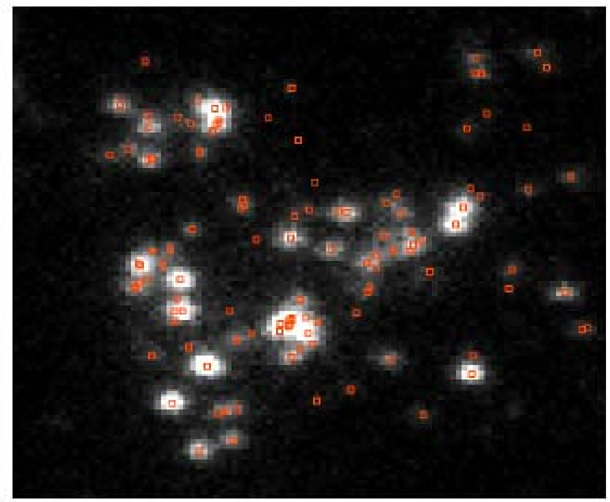


Figure 6. Expanded view (greyscale) of the UVIT CaF2 image of Field 2, 30 arcsec across, centered on the bright group of stars east of R.A. 00:44:40.5 Dec.+41:26:37 (J2000) (center of the image in Fig. 3). The red squares mark the positions of all stars from the PHAT survey with F275W Vega magnitude < 20.5.

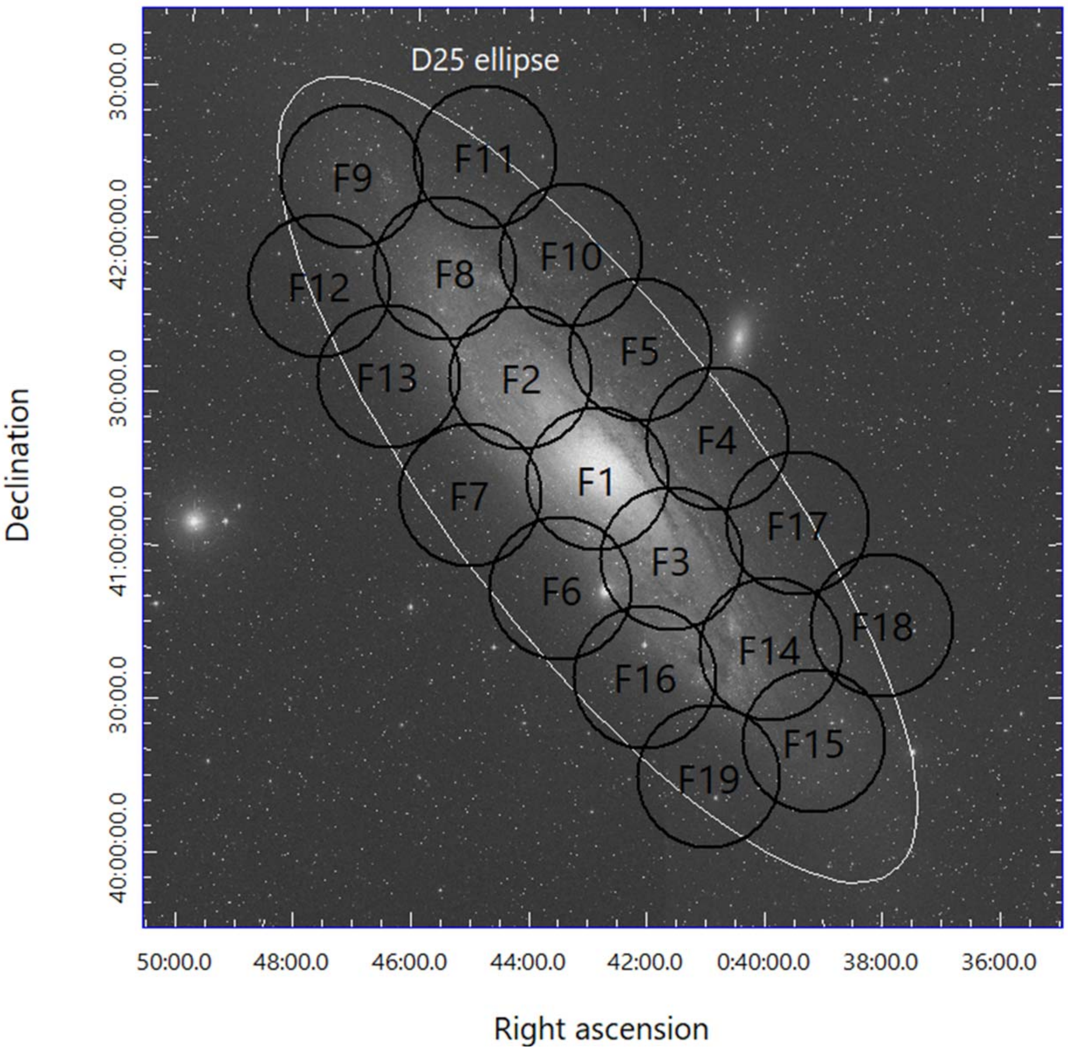
M31

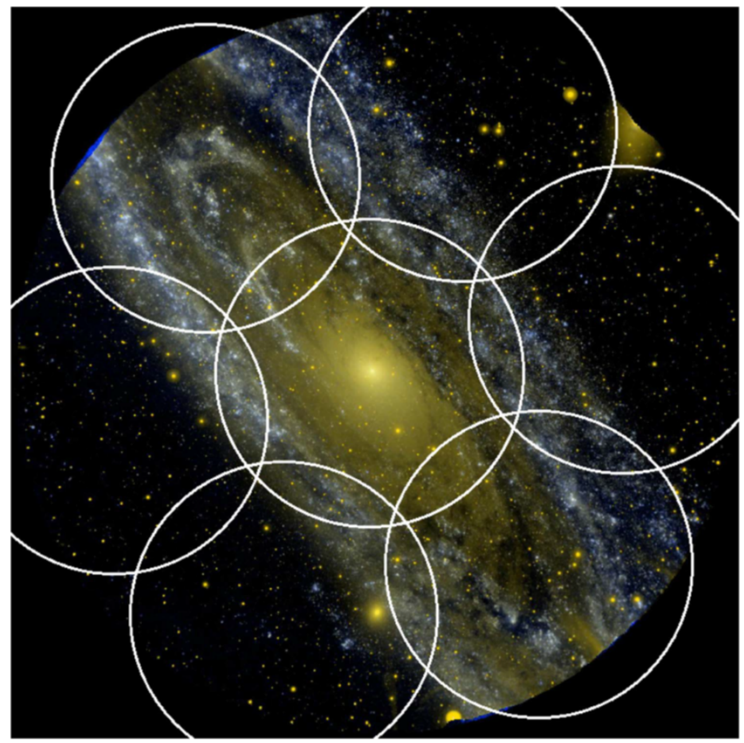
- **M31's inner spheroid** is primarily composed of red metal-rich stellar populations with broad red giant branches indicative of a **spread in metallicity and stellar age** (e.g. Durrell, Harris, and Pritchet 2004).
- Spectroscopic studies revealed a wealth of **substructure and significant inhomogeneity in M31's stellar halo** (e.g Richardson et al. 2009) and a **massive, metal-rich, extended disk** (Ibata et al. 2005).
- McConnachie et al. (2018) estimated that the various distinct substructures in M31's stellar halo were produced by **at least 5 separate accretion events within the last 4 Gyr**.
- Evidence for **a global burst of star formation 2-4 Gyr ago** (Williams et al. 2015).
- Measurements of [Fe/H] and [alpha/Fe] for 129 RGB stars in **the stellar halo of M31**, including its Giant Stellar Stream (Escala+2020) find a low [alpha/Fe] component **consistent with an accretion origin**

ESA website: R.Gendler image

M31 AstroSat/UVIT Survey

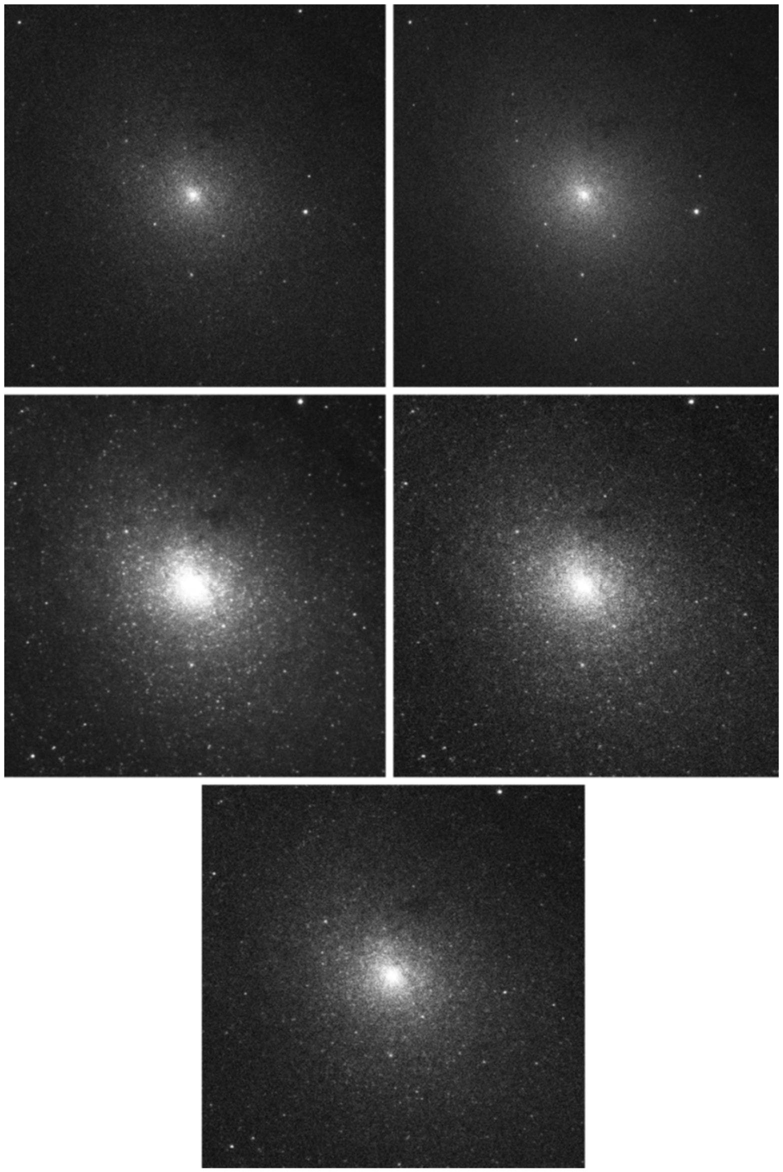
UVIT f.o.v 28’ diameter, 19 fields to cover M31
Wavebands: F148W (130-175nm), F172M (160-185nm),
N219M (190-245nm), N279N (270-290nm)
right: 7 central fields overlaid on GALEX image of M31 centre





M31 bulge FUV-NUV multi-filter UV analysis

(Leahy et al., 2021 IJAA, vol.11, p151-174)



Contours: M31 bulge is elliptical

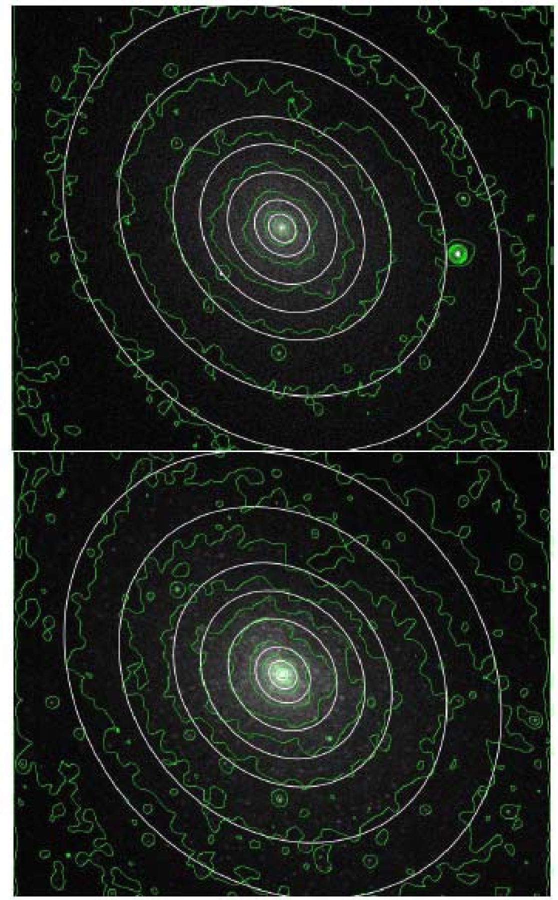
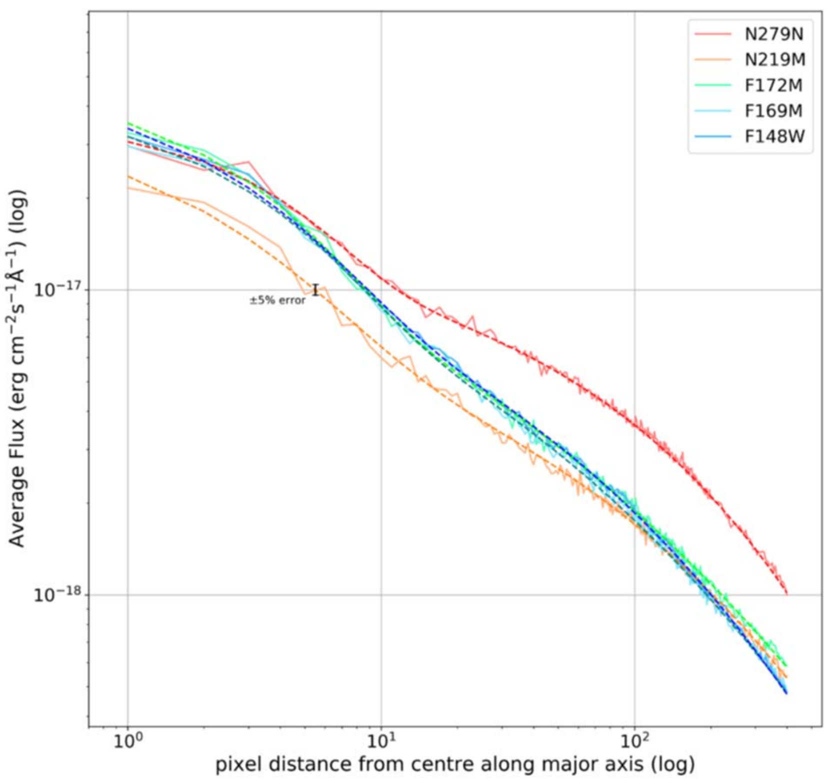


Figure 2. The bulge of M31 in N279N (top) and F148W (bottom) with contours drawn in green using the ds9 image viewer, and a subset, drawn in white, selected from the 240 ellipses used to create the elliptical profiles. The images are 370"E-W by 330"N-S.

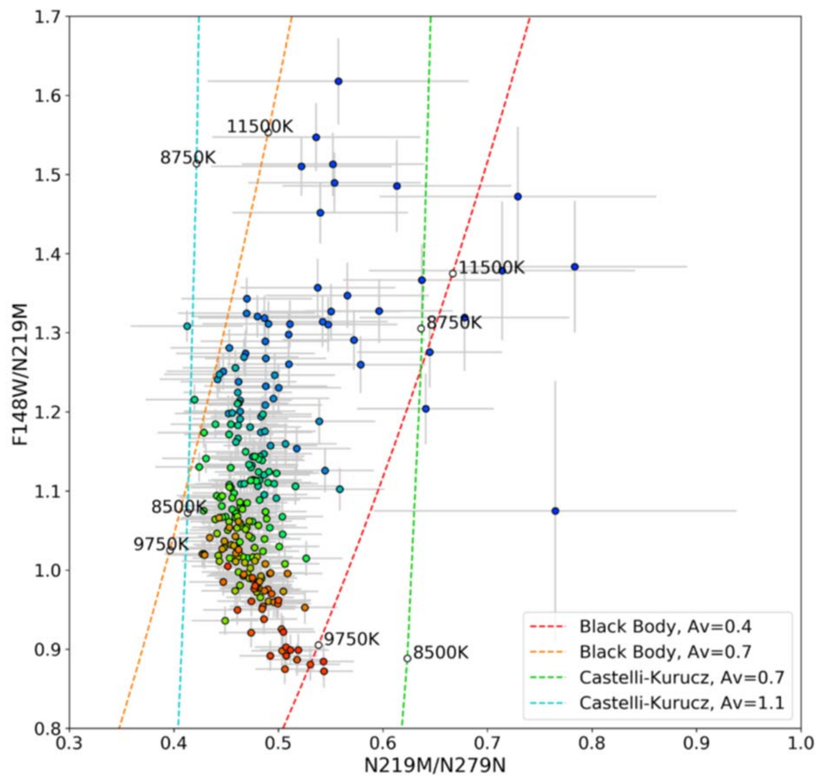
Elliptical surface brightness profile: well fit by (outer) Sersic plus (inner) Gaussian



Colour-colour diagram:

Inner bulge is hotter (12,000K blackbody or 9000 K stellar atmosphere),

Outer bulge is cooler (10,000K blackbody or 8600 K stellar atmosphere)



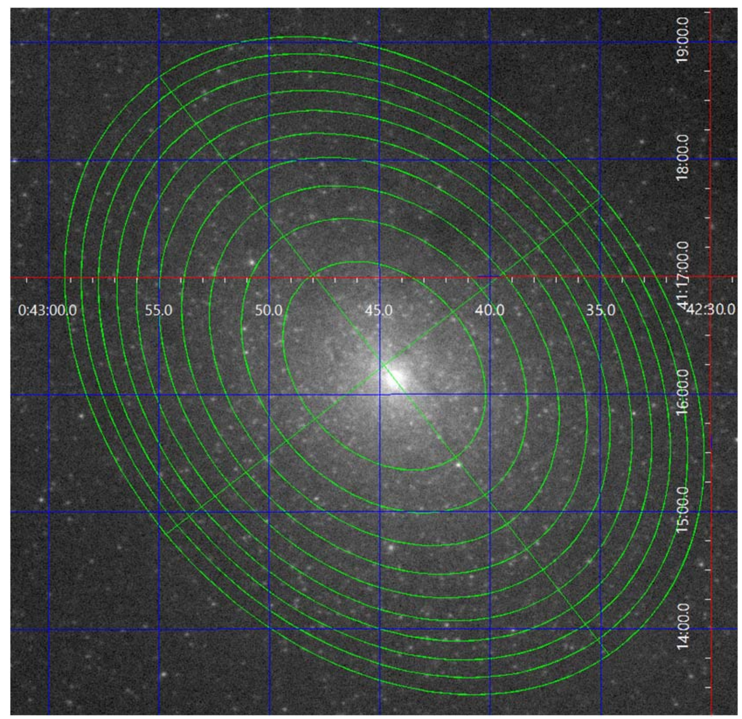
Stellar Population Analysis I (CIGALE)

Extract FUV, NUV, optical, NIR, FIR (17 bands) magnitudes for the bulge, defined by an ellipse with semi-major axis of 188“.

The large ellipse was sub-divided into 10 annuli (40 quadrants) of equal-area to study spatial variations.

Table 1. Overview of Data Used

Instrument	Filter	Wavelength (μm)
UVIT	F148W	0.1481
UVIT	F169M	0.1608
UVIT	F172M	0.1717
UVIT	N219M	0.2196
UVIT	N279N	0.2792
SDSS	u	0.3543
SDSS	g	0.4770
SDSS	r	0.6231
SDSS	i	0.7625
SDSS	z	0.9134
IRAC	Channel 1	3.6
IRAC	Channel 2	4.5
PACS	Blue	70
PACS	Red	160
SPIRE	PSW	250
SPIRE	PMW	350
SPIRE	PLW	500

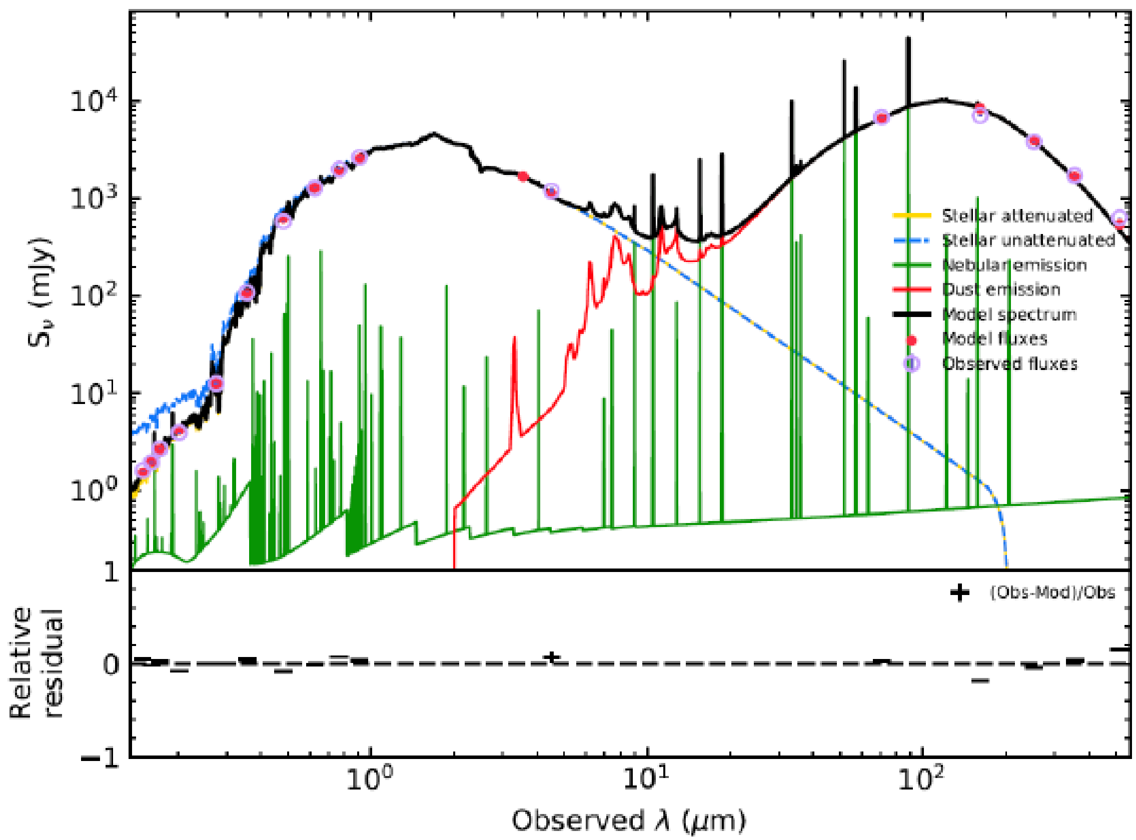


Cigale Analysis

The multiband photometry is modeled using the public CIGALE code (Burgarella et al 2005, Boquien et al, 2019)

CIGALE includes

- stellar emission,
- nebular emission,
- dust emission,
- dust attenuation



Cigale Analysis results

With Bruzual & Charlot (2003) SSP models
Best fit SFH is '2-burst' model (sfh2exp)
Best fit AGN contribution is zero

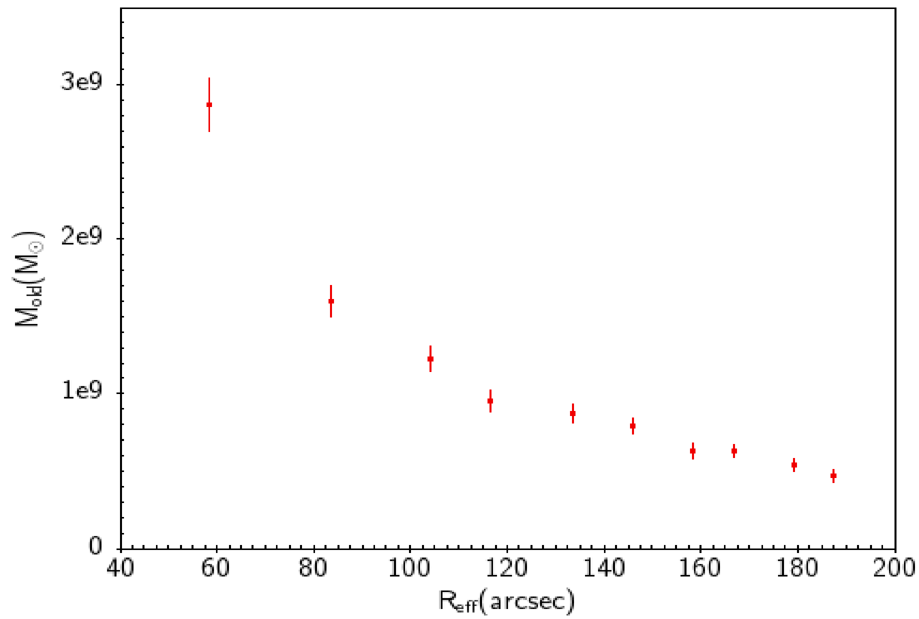
Many parameters in CIGALE:
8 parameters (below) consistent with constant over the 10 regions.

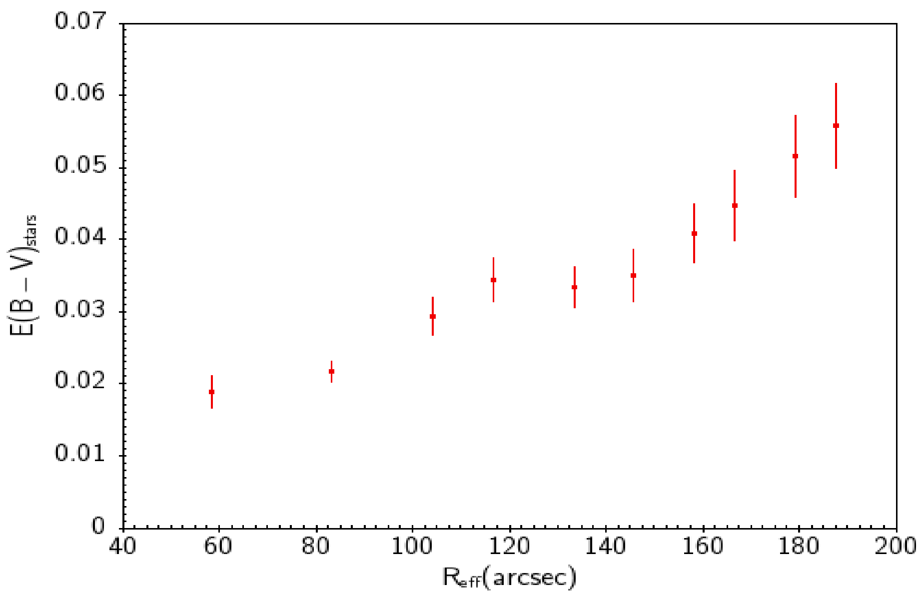
Table 3. M31 Bulge CIGALE Parameters Consistent with Constant

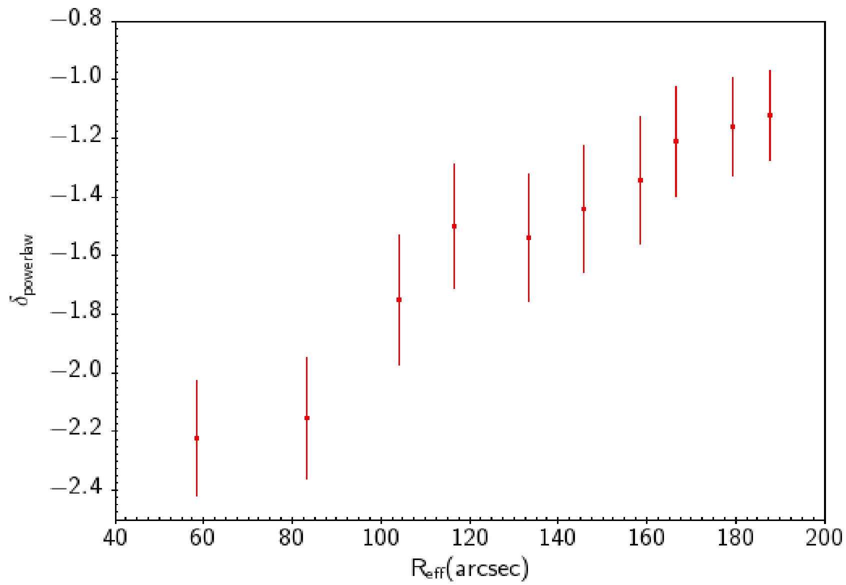
Input Parameter	Mean	Mean Error	Standard Deviation
$E(B\text{-}V)_{factor}$	0.382	0.120	0.041
α_{dust}	1.952	0.052	0.041
age_{main} (Myr)	12170	772	120
Tau_{main} (Myr)	446	81	2.6
age_{burst} (Myr)	602	107	57
Tau_{burst} (Myr)	24.9	11.1	0.25
f_{burst}	0.0030	0.0011	0.0006
Z	0.020[a]	8×10^{-5} [a]	1×10^{-6} [a]
Derived Parameter	**Mean**	**Mean Error**	**Standard Deviation**
M/L ($M_\odot/L_\odot$)	1.90	0.15	0.04

Cigale Analysis

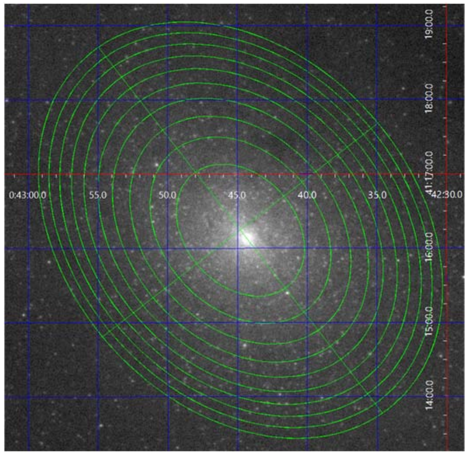
Variable between regions:
stellar mass (right)
extinction (below)







Stellar Population Analysis II (multiple SSPs)



The aims (beyond CIGALE):

i) to include more than 2 SSPs

ii) to allow each SSP to have its own metallicity and extinction

How to achieve this: write our own modelling/fitting code using existing SSP models.

Simplifying assumptions: no nebular or dust emission.

Use the same multi-band magnitudes sets, but omit FIR because it is dominated by dust emission.

-For the whole bulge as above.

-For the same 10 equal-area annuli.

Here, we use the SSPs using the **Padova stellar models**, calculated using the CMD 3.4 online tool at http://stev.oapd.inaf.it/cgi-bin/cmd. In CMD 3.4, we used the recommended options: PARSEC evolutionary tracks [18], version 1.2S, for pre-main sequence to first thermal pulsation or carbon ignition, and COLIBRI [19] for thermal pulsation-asymptotic giant branch,evolution, ending at total loss of the envelope.

Multiple SSP Analysis results

Results:
2 SSPs fit outer 6 annuli
Inner 4 annuli fit better with 3 SSPs

Metallicity of each SSP is different
Extinction of each SSP is different

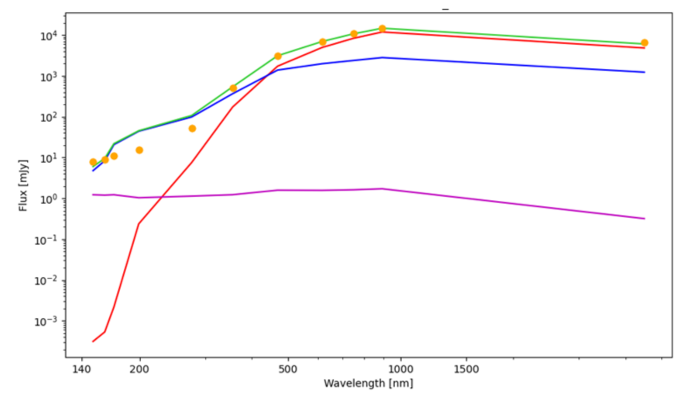


Table 6. 3-SSP Best-Fit Parameters[a] for the M31 Bulge UV to NIR Data

Region[a]	R_{out} ($''$)	χ^2	M_1^b / M_3^b ($M_\odot$)	age_1 / age_3 (yr)	$\log(Z_1/Z_\odot)$ / $\log(Z_3/Z_\odot)$	$E(B-V)_{1,2}$ / $E(B-V)_3$	M_2^b ($M_\odot$)	age_2 (yr)	$\log(Z_2/Z_\odot)$
Ann1	58.4	8.5E4	7.6E9	1.0E10	0.30	0.18	2.4E8	6.3E8	-0.02
			1.1E4	1.4E7	-0.50	0.10			
Ann2	83.4	6.5E4	4.1E9	1.0E10	0.30	0.18	1.4E8	6.3E8	-0.01
			3.0E3	2.4E7	-0.79	0.22			
Ann3	104.2	5.9E4	3.1E9	1.0E10	0.22	0.21	1.2E8	6.1E8	0.03
			2.0E3	2.6E7	-0.75	0.24			
Ann4	116.7	5.5E4	2.7E9	1.0E10	0.30	0.19	9.5E7	6.1E8	0.03
			1.8E3	2.7E7	-0.76	0.25			

Summary of M31 Bulge SFH Analysis

Using CIGALE and our multiple-SSP modelling code, we measure the star formation history and metallicity of the bulge of M31.

Ages of old and intermediate age SSP better determined by CIGALE, metallicities and extinction better determined by our code.

Compare results to those from Dong+2018, Dong+2015, Saglia+2018, etc. to derive a consistent picture

The bulge has 3 stellar components:

-a dominant 12 Gyr old population ([Z/H]=0.3),

-a small (~1% by mass) 700 Myr old population ([Z/H]=0),

-in the central 100”, a small (~10^{-6} by mass) ~25 Myr old population ([Z/H]=-0.7).

The metallicity decreases as the stellar populations are younger (agrees with Dong+2018)

This is surprising, but can be explained by the merger history of M31, where the newer populations form from more pristine infalling gas.

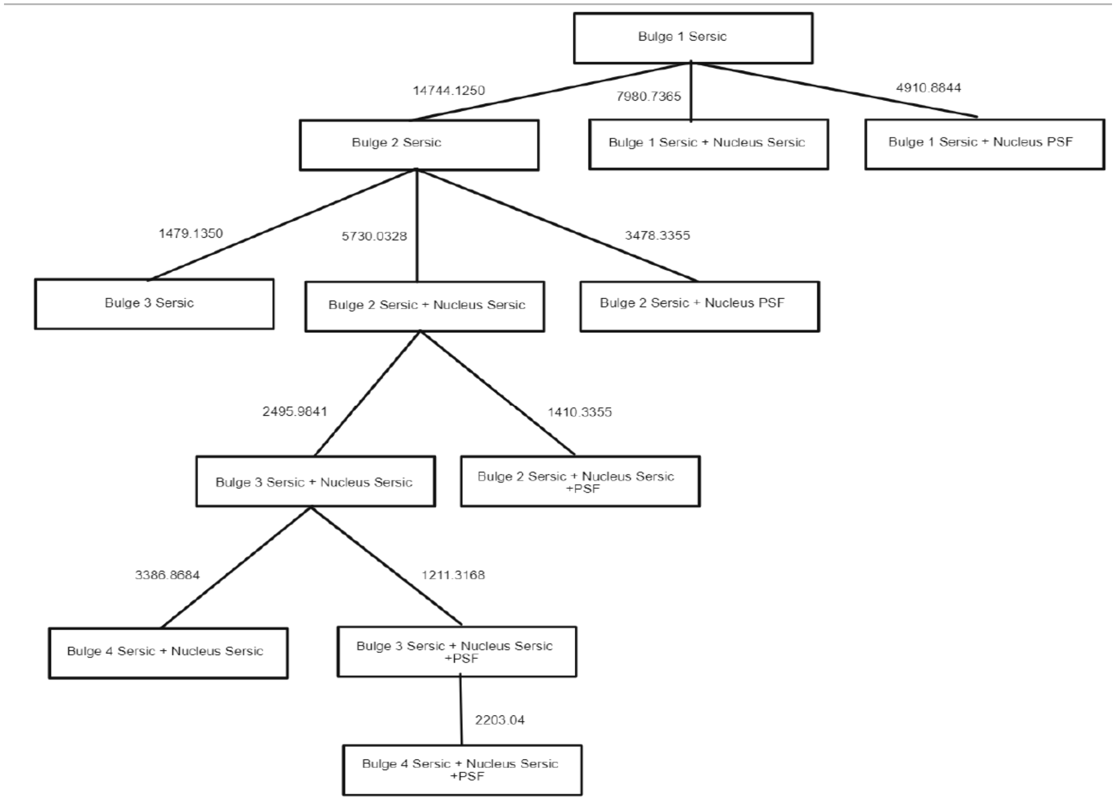
Previous work: fit bulge with single Sersic functions in optical or IR; multi-compnent fit to nuclear region (Peng 2002)

Leahy et al., 2021 IJAA: fit FUV and NUV with elliptical profile with plus Sersic (large scale) plus Gaussian (small scale)

Current work: use GALFIT to fit bulge and nucleus

Results: FUV (150nm) model: The bulge modelled by 4 Sersic functions with different R_e, centres, Sersic index n; the nucleus is modeled (at 1” resolution) by 1 Sersic function plus psf.

M31 Bulge Spatial Analysis



M31 Bulge Spatial Analysis

For FUV (150nm): the bulge model is shown at top right (4 Sersic functions). Box size is 420”x420”.

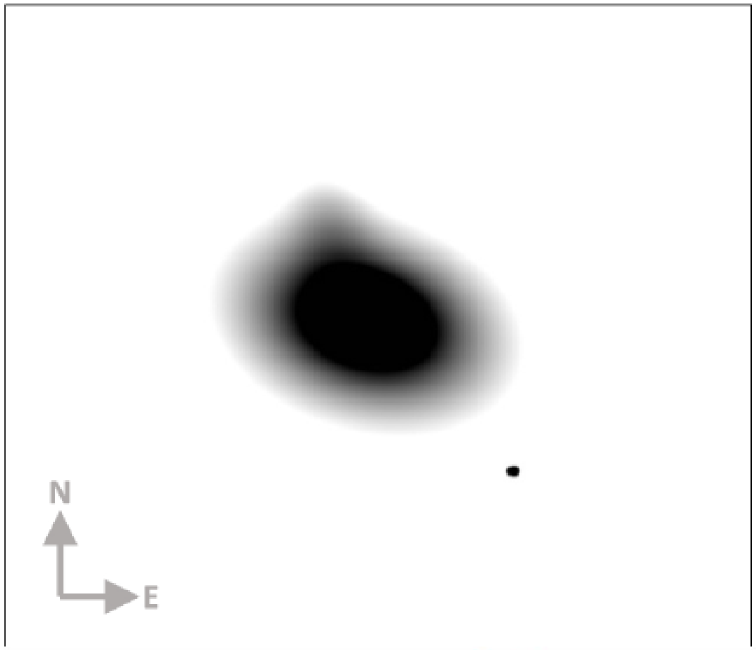
i) The bulge is asymmetric.

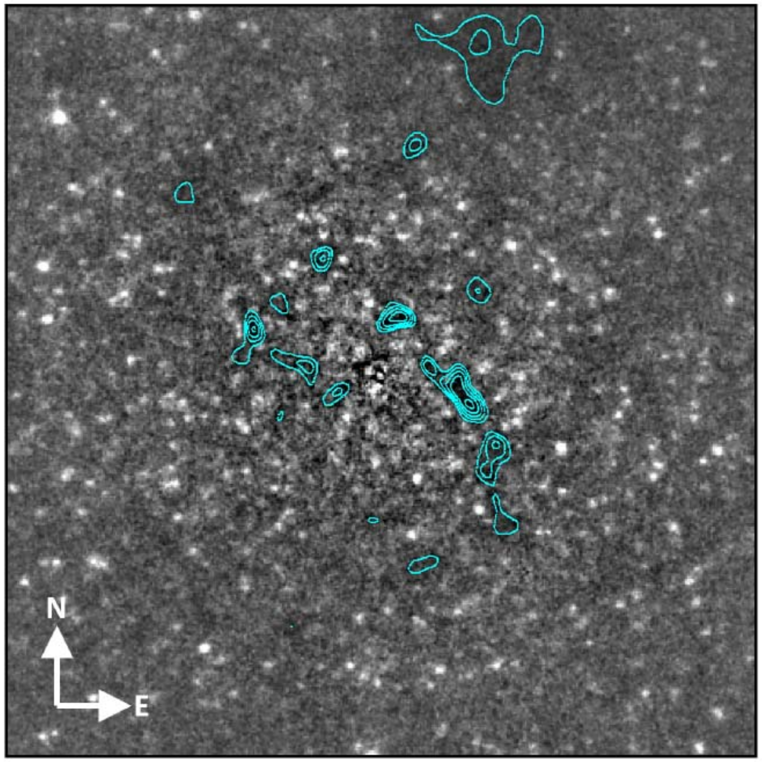
The residual after subtraction of bulge and nucleus model is shown at bottom right.

ii) The residuals show many compact clumps throughout: most (>90%) are not identified with known globular clusters.

iii) The dust lanes in the bulge are clearly seen (previously seen by Dong+ 2016)

(further analysis underway)





Summary of M31 Bulge Analysis

SFH analysis:

The bulge has 3 stellar components

The metallicity decreases as the stellar populations are younger

This can be explained by the merger history of M31, where the newer populations form from more pristine infalling gas.

Spatial analysis

The bulge is asymmetric.

The residuals show many compact clumps throughout (their nature TBD).

Dust lanes in the bulge are clearly seen.

This work funded by the Canadian Space Agency