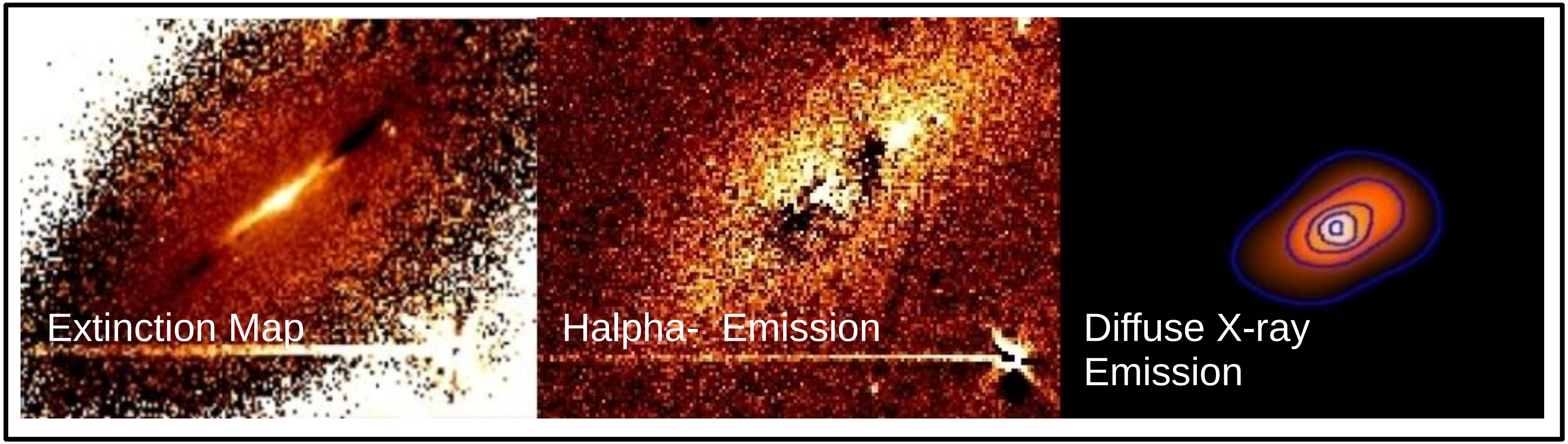
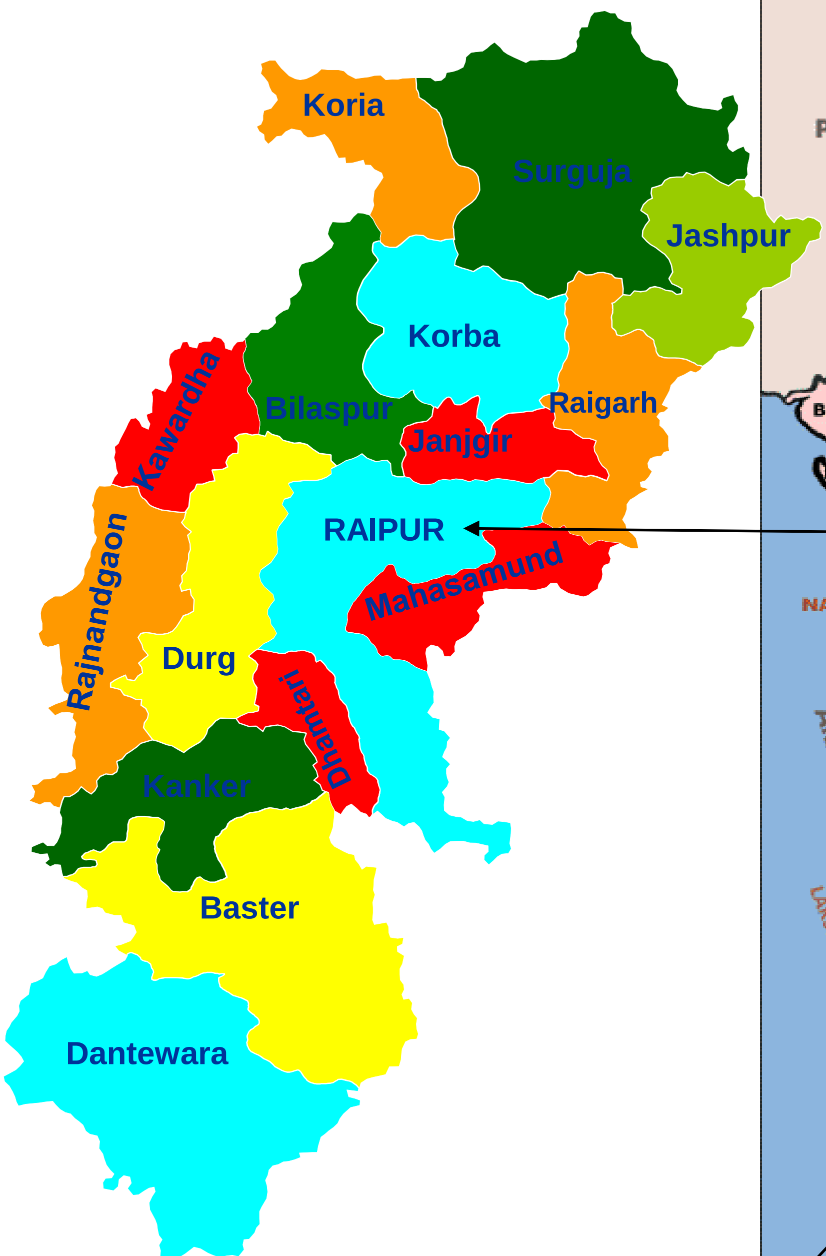
Dust and Gas in nearby Early-type Galaxies



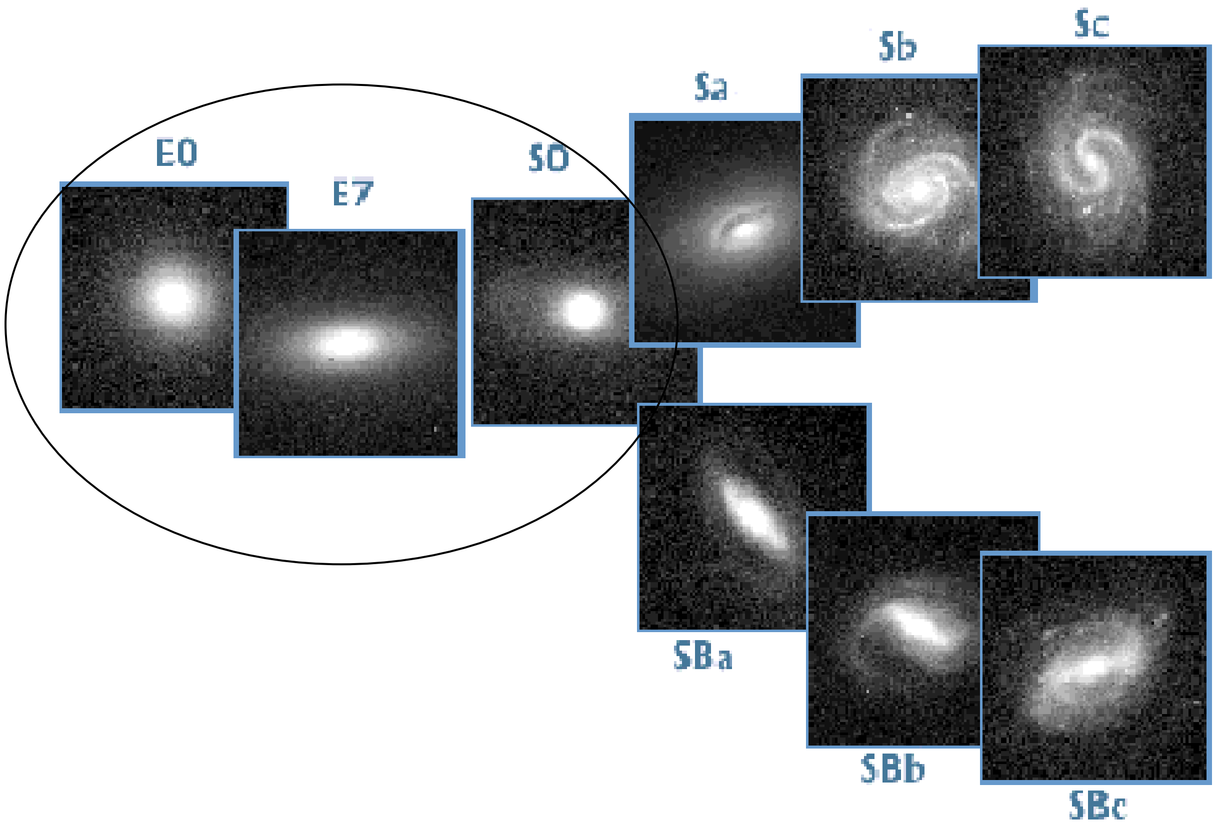
NGC 5866 ***NGC 5866***

Samridhi Kulkarni and S. K. Pandey
Pt Ravishankar Shukla University, Raipur, India
(Email : skp@iucaa.ernet.in, proskp@gmail.com)

CHHATTISGARH



Early type Galaxies



Once believed to be devoid of Interstellar matter (gas and dust) as well as absence of ongoing star formation, Early type galaxies are now considered to contain complex, multiphase ISM.


M87 © Anglo-Australian Observatory
Photo by David Malin

The Multi-Phase ISM in Early-type(E&S0) Galaxies

All forms of ISM present in Spirals have been detected in Early type Galaxies but in different proportions.

Cool Gas (HI) and Molecular Gas (CO)

$T \leq 10$ K,
detected in 8-10% of E/SO
Mass $\leq 10^7 M_\odot$

Ionized Gas

$T \sim 10^4$ K
detected in ~70% of E/SO
Mass 10^3 - 10^5 $M_\odot$

Dust

$T \sim 10$ - 100 K
detected in > 50% of E/SO
Mass 10^4 - 10^7 $M_\odot$

Hot Gas

$T \sim 10^7$ K
detected in ~70% of E/SO
Mass 10^9 - 10^{11} $M_\odot$

Except the Hot phase of ISM, the probable origin for all other phase is considered to be external.

The Dust

- *Dust is found every where, in different environments including galaxies, quasars, AGNs etc.*

- *An important raw material for star formation: dust acts as catalyst for the formation of molecules; always associated with gas*

- *Dust are formed at late stages of stellar evolution; composed mainly of elements such as carbon and silicate compounds, and various kinds of ices with grain sizes ranging from a few hundred A° to a few μm.*

Objectives :

- *Our main objective is to study the wavelength dependence of dust extinction and compare with that of the dust in our galaxy.*

- *Examine the relationship of dust with the different phases of the ISM, which is expected to provide better understanding of the nature, origin and evolution of ISM in early-type galaxies.*

Properties of dust

The Extinction Law : wavelength dependence of the dust extinction, the extinction curve

Direct Method:

- Multicolor stellar photometry of individual stars ; involves comparison of the flux distribution of a reddened star with that of an unreddened star of the same spectral type and same luminosity class.

- $A_\lambda = m(\lambda) - m_0(\lambda)$

- selective extinction between B and V = $E(B\text{-}V) = A_B - A_V$

=>Works well if individual stars are resolved and sufficiently bright over a wide range of wavelength for the determination of A_λ as a function of λ. (MilkyWay, SMC, LMC)

- For the Milky way one finds that

(i) The extinction curve varies linearly with λ^{-1} in the optical region

(ii) The galactic extinction curve is mainly function of $R_v = A_v/E(B-V)$; the ratio of total extinction in V to the selective extinction between B and V.

➔R_v = 3.1 (Milky way), 2.7(SMC), 3.2(LMC)

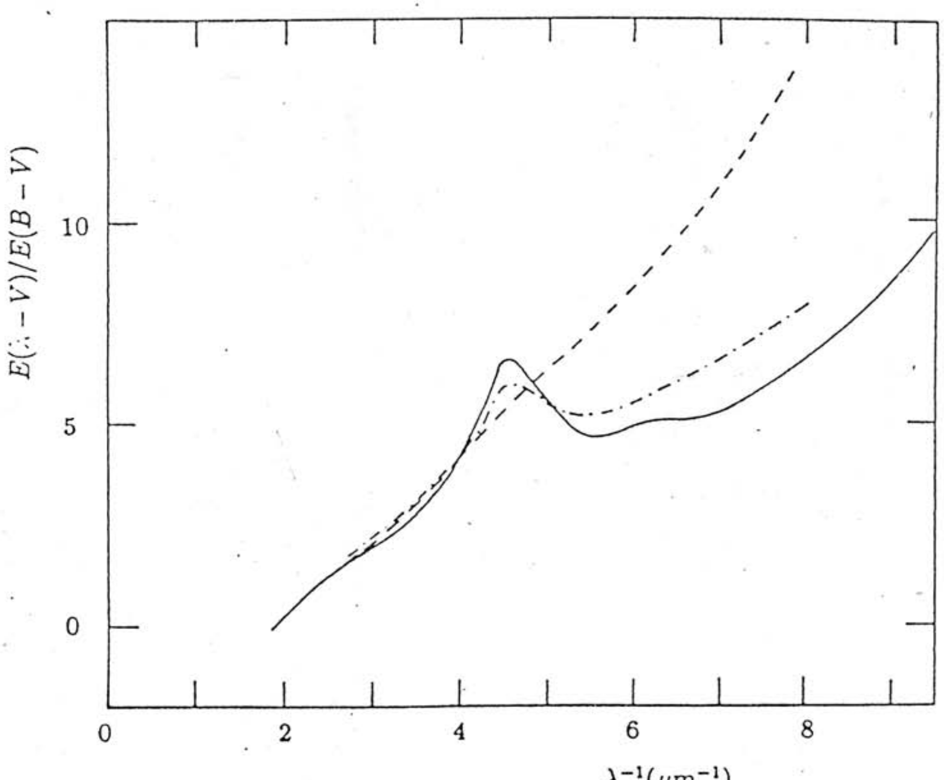


Figure 9.3: Extinction laws in the Galaxy (full curve), the Large Magellanic Cloud (dash-dot curve) and the Small Magellanic Cloud (dashed curve). Adapted from E. L. Fitzpatrick, *Interstellar Dust*, IAU Symposium 135, p. 37 (1989).

•***Indirect Method*** *: Comparing the actual observed light distribution from a galaxy with that expected in the absence of dust, as a function of λ will provide an estimate of* A_λ

•***Extinction Map*** *: prepared by dividing the original image of galaxy in particular pass band by, its corresponding smooth dust free model image, generated using the ellipse fitting procedure in STSDAS, when the dust occupied regions were masked off.*

$$A_\lambda = -2.5 \times \log [I_{\lambda,obs}/I_{\lambda,model}]$$

here A_λ *is the amount of extinction in a particular pass band λ (=B, V, R, I).*

=>Early-type galaxies are ideally suited because of their inherently smooth distribution of light (Goudfrooij 1994).

Dust Extinction

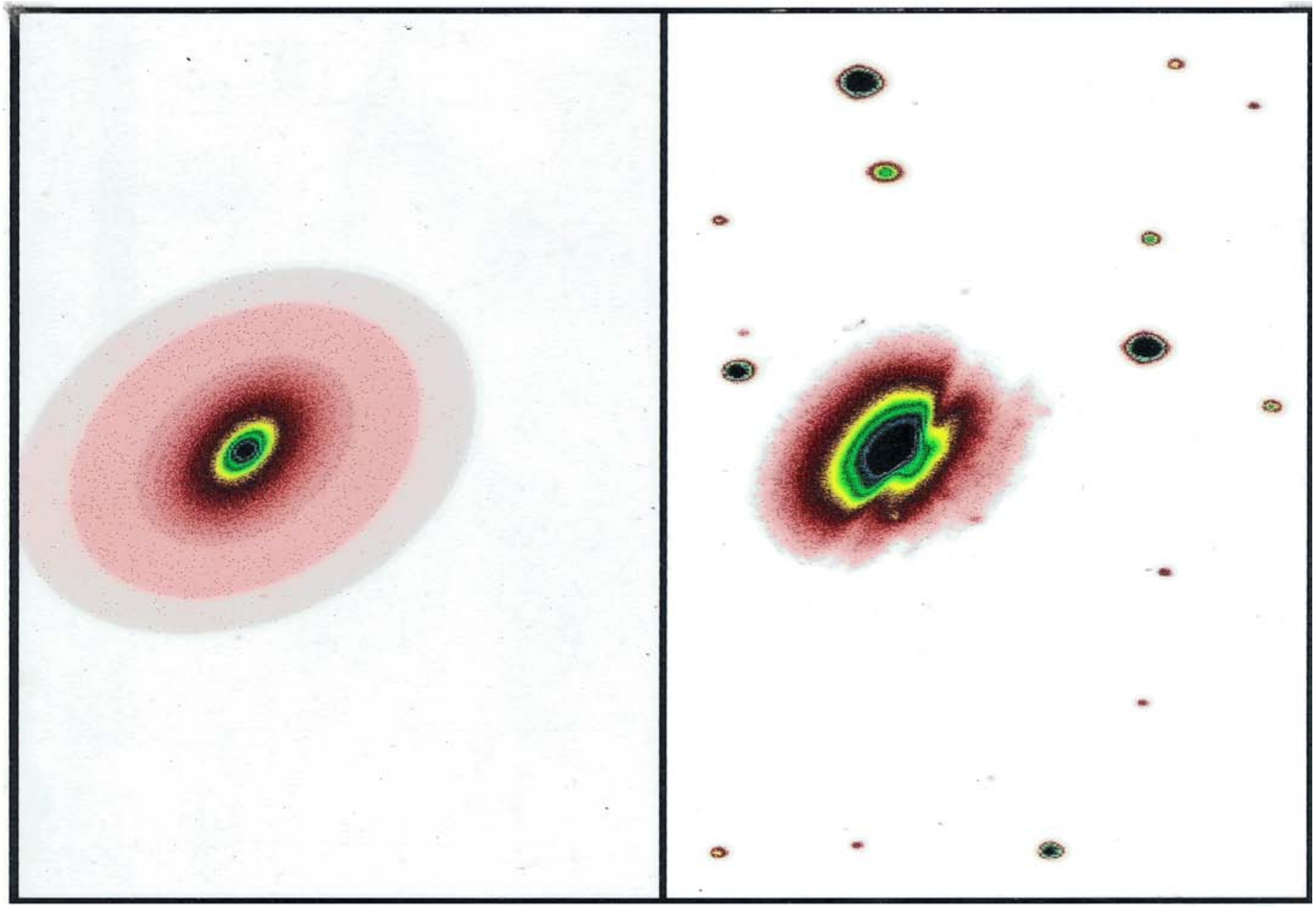
•Extinction maps:

Quantitative measure of the dust extinction

$A_\lambda = -2.5 \log (I_{\lambda,obs}/I_{\lambda,model})$

Here, $I_{\lambda,model}$
→ from ellipse fitting

Example→



Surface Photometry

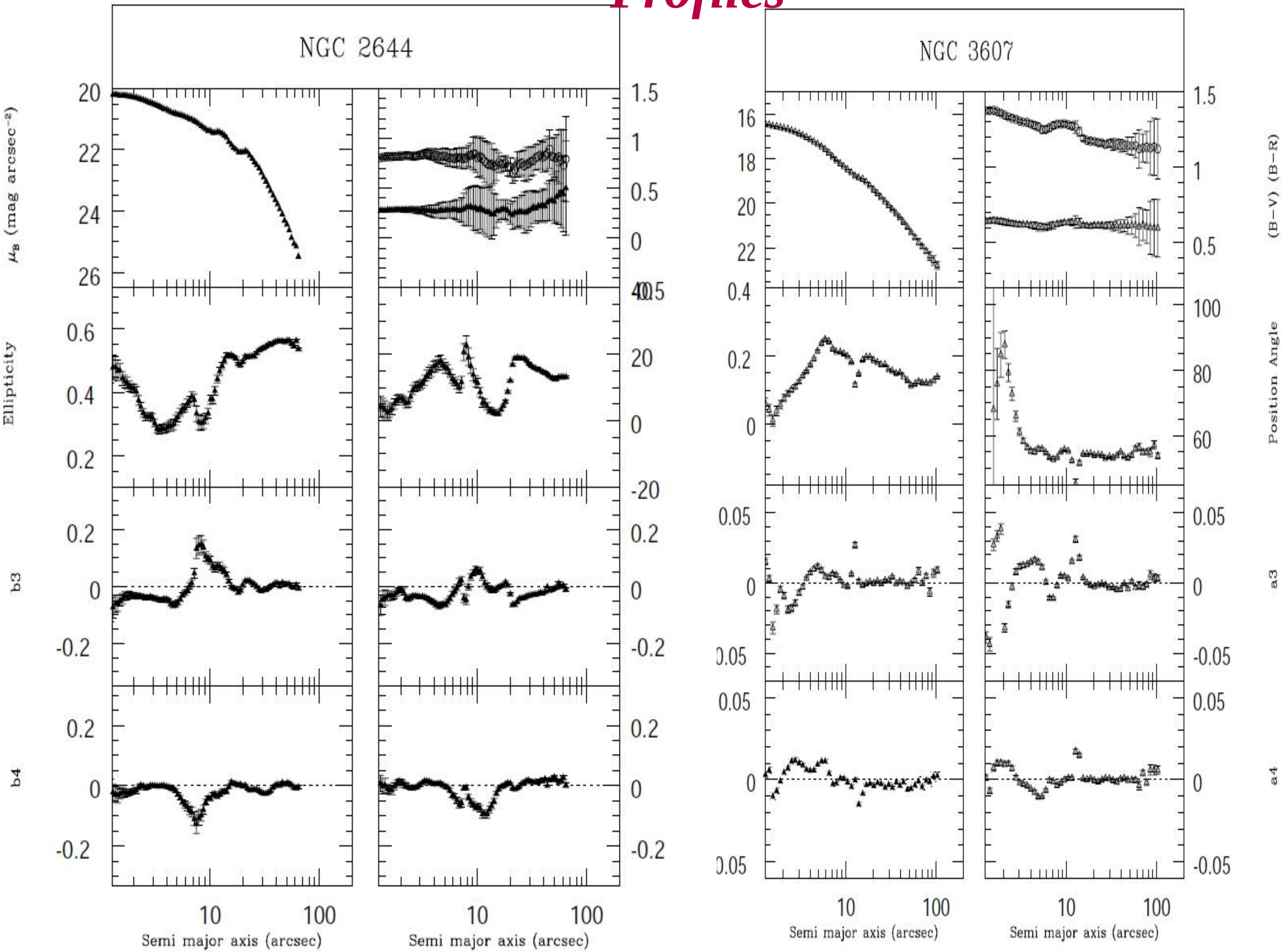
- *Surface photometry is usually done by fitting ellipses to the isophotes, as the isophotes of galaxies, especially, of ellipticals and lenticulars are quite close to ellipses in the zeroth order!*

(Isophotes : contours of constant brightness).

- *Used to extract parameters characterizing different components of a galaxy.*

- *Results are expressed in the form of surface brightness profiles, color profiles as well as profiles of geometric parameters.*

Profiles

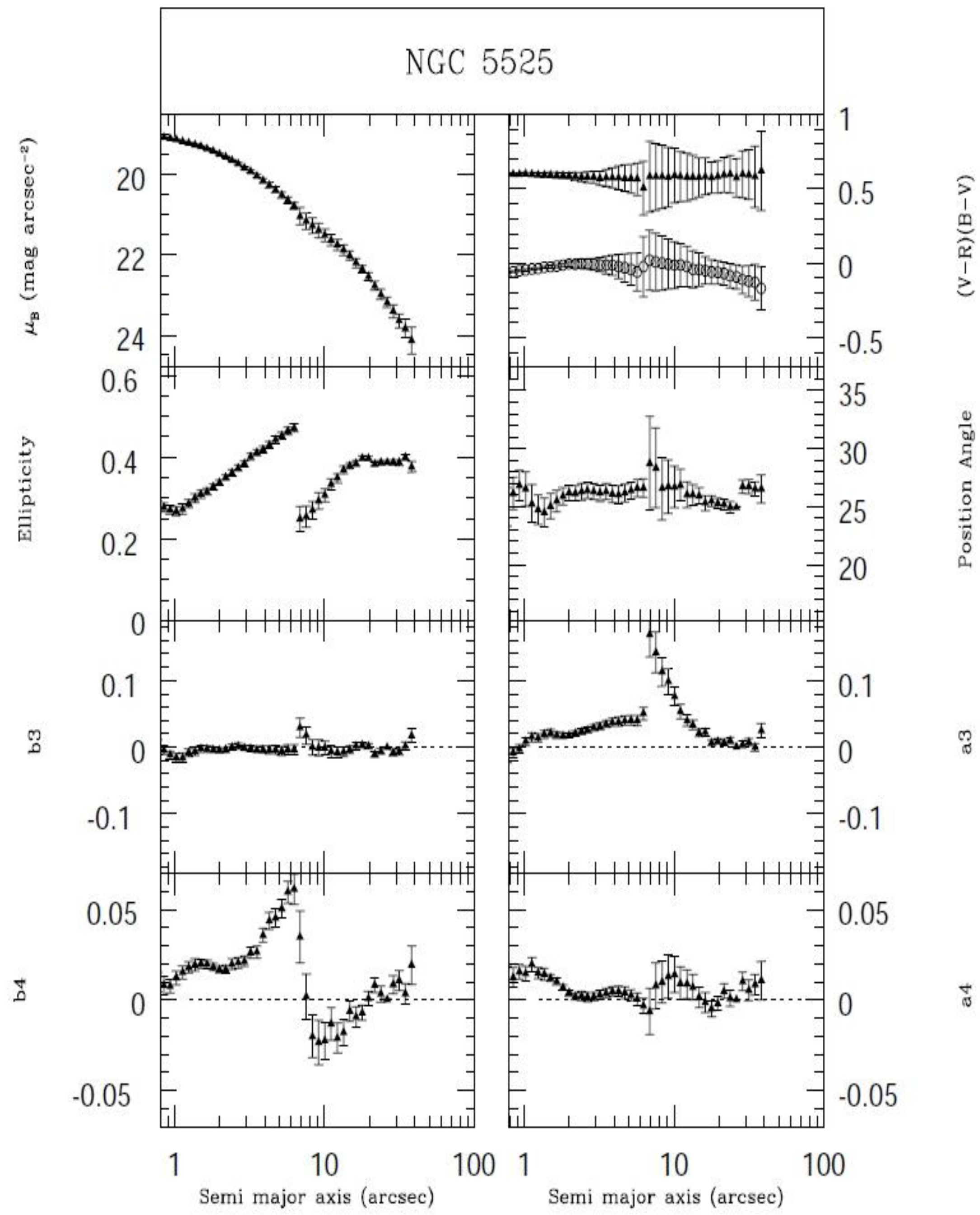


NGC 2644
NGC 3607
μ_B (mag arcsec^{-2})
Ellipticity
b3
b4
(B−V) (B−R)
Position Angle
a3
a4
Semi major axis (arcsec)

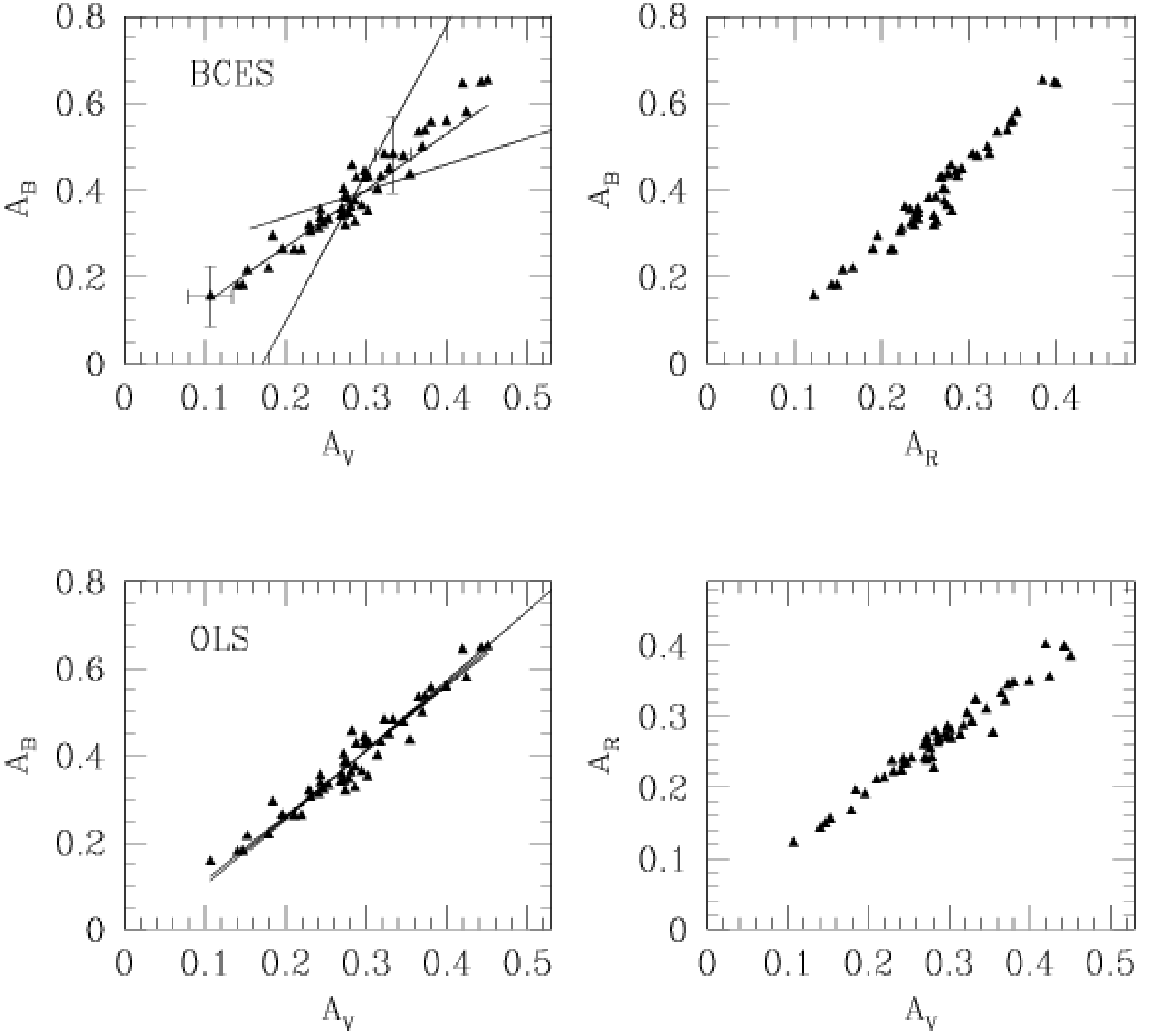
Profiles

- *Noticeable kink in surface brightness profile can be traced due to presence of strong dust obscuration.*

- *Higher order Fourier Coefficients A3, B3 are considered to be good tracer for presence of dust in galaxies (Peletier 1989, Goudfrooij et al. 1994a) and regions of significant deviations in them, coincide with the location of dust absorption features within the galaxies.*



- $E(B-V) = A_B - A_V$
  (local values)
- Linear regression between different extinction values (A_x vs A_y, $x \neq y$)
- Obtain best fitting slopes (A_B/A_V etc) →

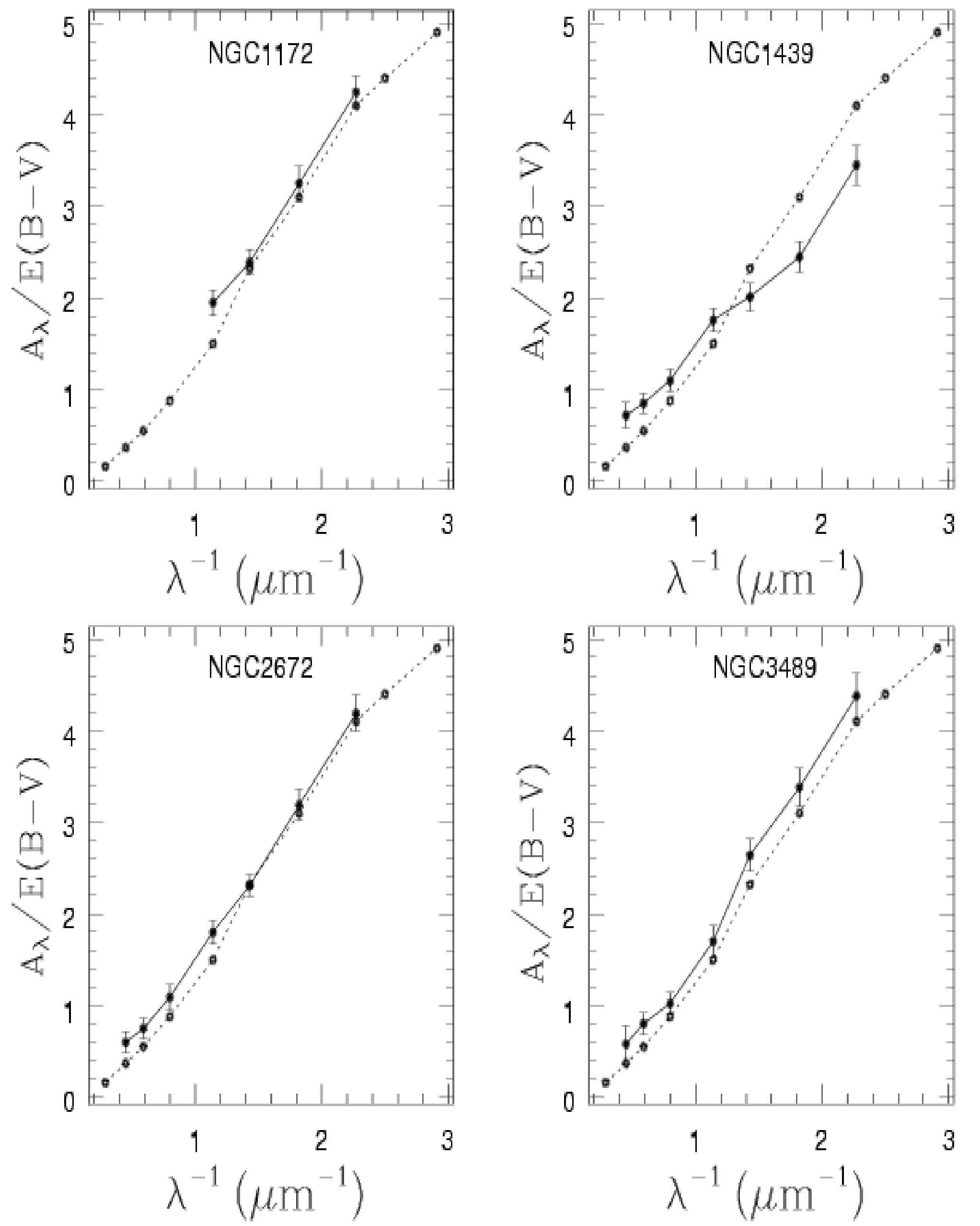


The Extinction Curve

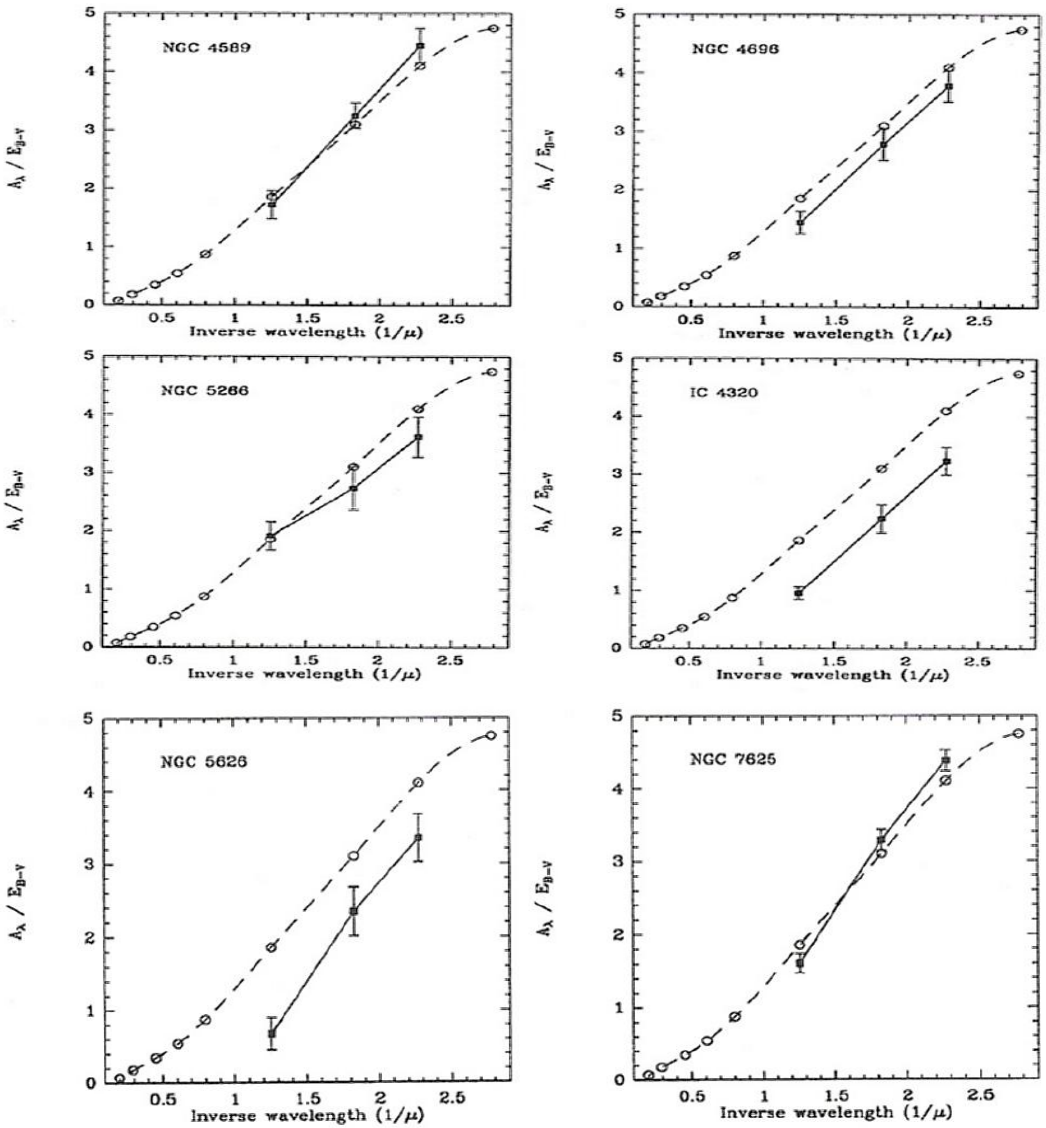
- Compute A_λ /E(B-V)

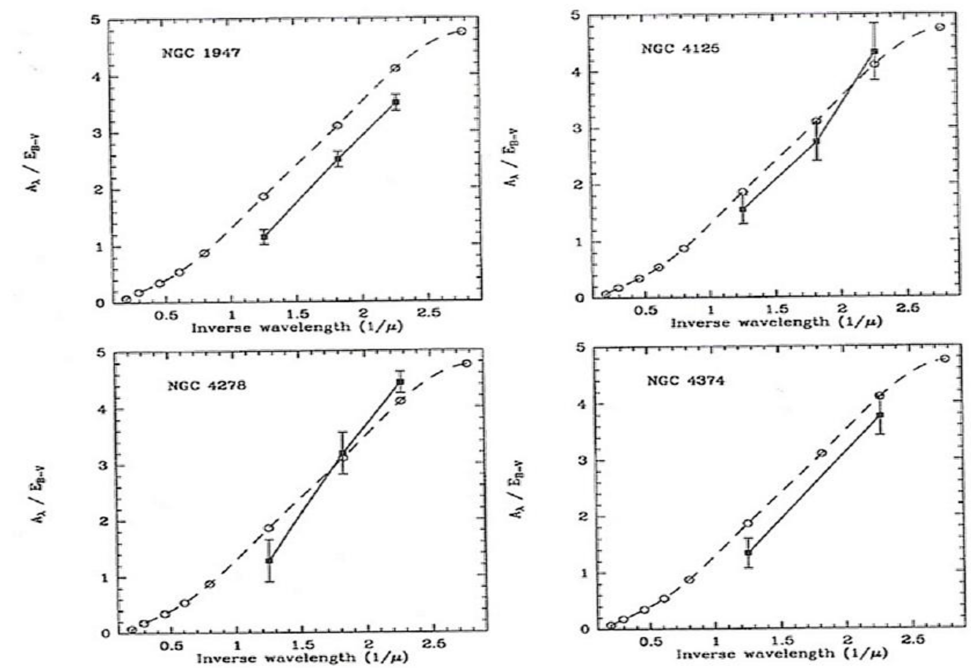
- Extinction curve: A_λ /E(B-V) vs. λ^{-1} →

→ nearly parallel to the Galactic extinction curve in most galaxies

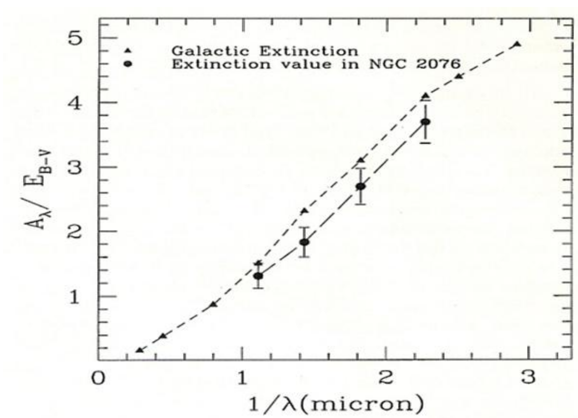


Extinction curves …



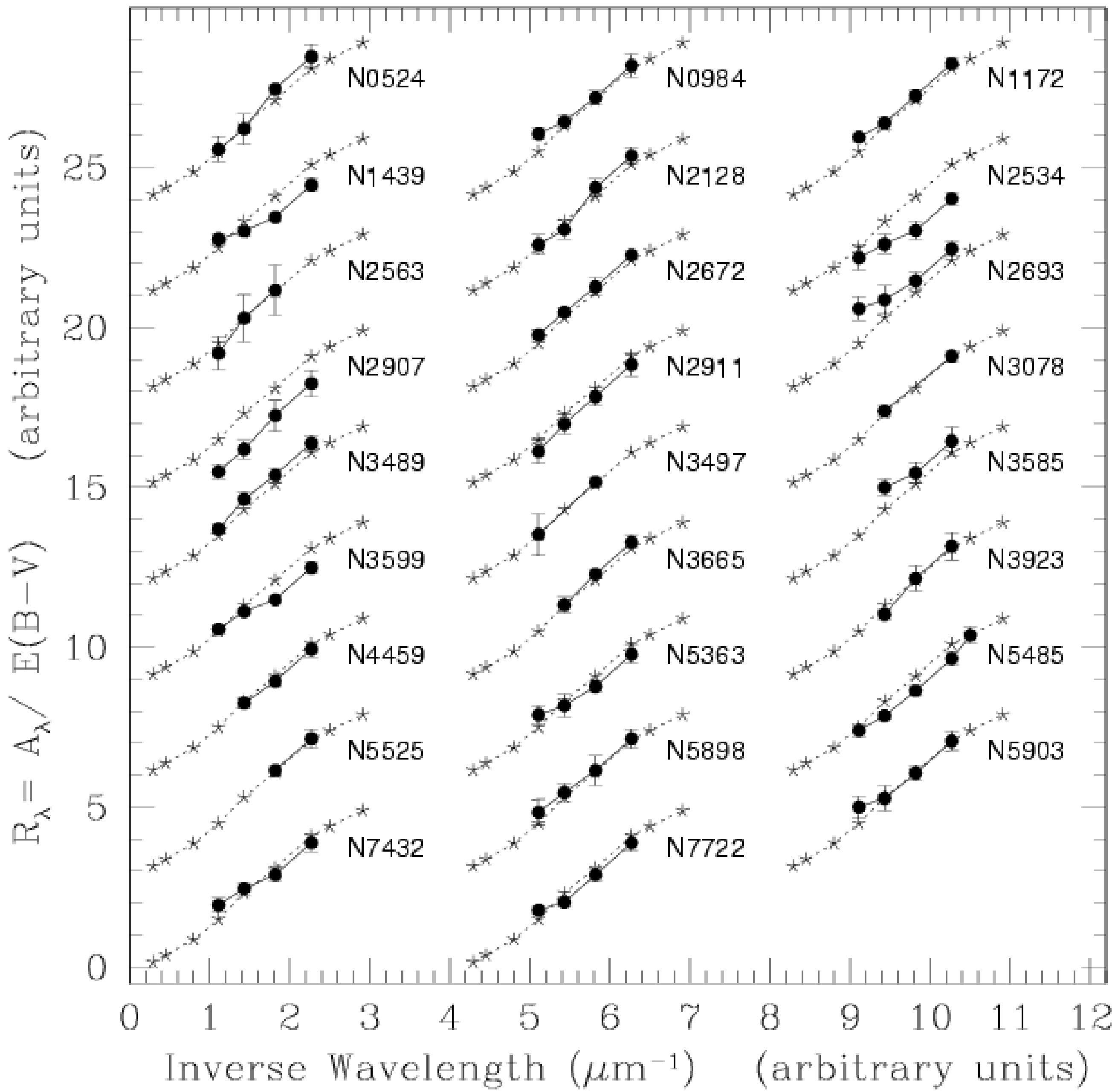


(Goudfrooij et al. 1994b)



(Sahu, Pandey & Kembhavi 1998)

Extinction Curves



Patil et al. (A&A, 2007)

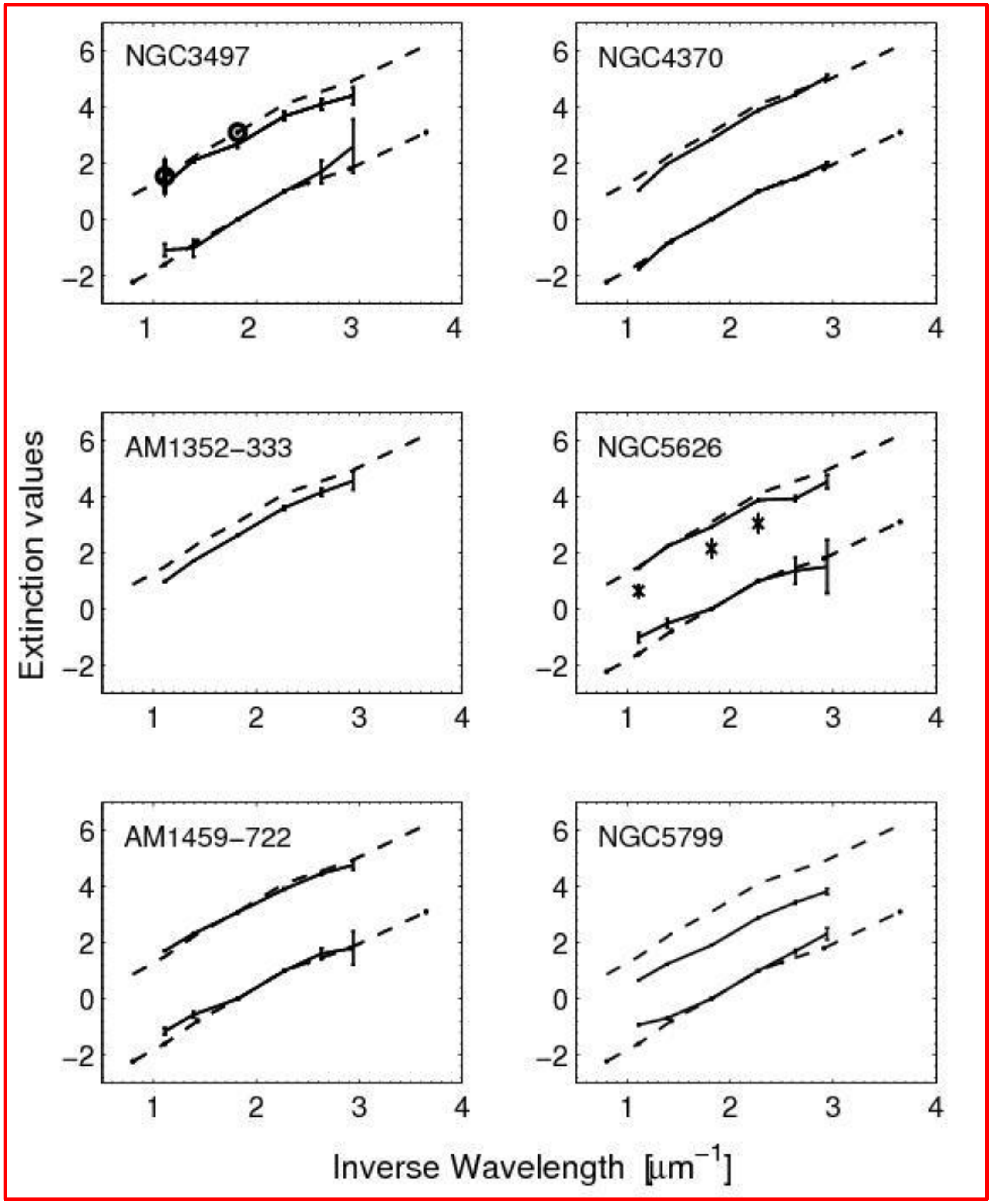
Extinction law in extragalactic environment: some results

- The extinction curves for a majority of galaxies run parallel to that of the Galactic curve
  ☞ Extinction properties in extragalactic environment are identical

- Smaller "R_V" (2.03 to 3.46) found in large scale dust lane galaxies (NGC 1947, 2076, 2534, 2907, 4626, 5363, 7722, IC 4320, etc.)
  ☞ "Large" grains responsible for dust extinction on average are "smaller" (~25%) than the canonical grains in our Galaxy

- Galaxies with irregular, arc shaped dust morphology have "normal" grains

Study of Dust with SALT …



- Extinction curves derived by Finkelman et al.(2008, 2010) run parallel to the canonical MW curve, implying similar properties as that in the MW

They obtained R_V=2.82 ± 0.38, indicating that characteristic grain size in dust-lane galaxies is smaller than that in the Milky Way; confirm our results (Patil et al.2007)

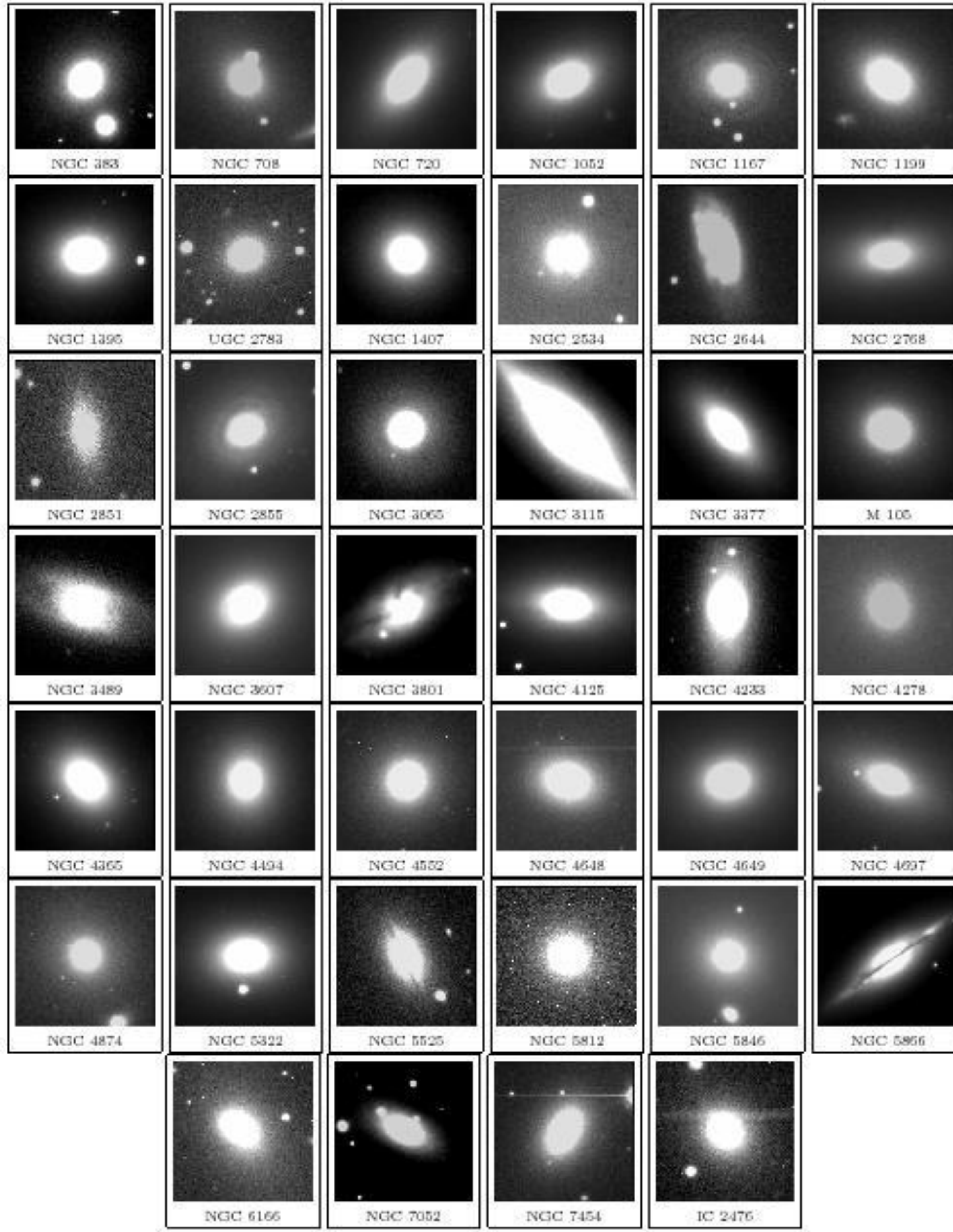
Present Study:

The Sample

- *Our sample consists of 40 nearby early -type galaxies E/SO.*

- *Observed using HCT (Hanle) and IGO (Pune)*

- *Containing small or large quantity of dust or ionized gas.*
- *Most of these galaxies are chosen from Brown and Brggman(1998) consisting of x-ray bright galaxies . Other objects were selected from the recent studies of E/SO with dust or ionized gas.*



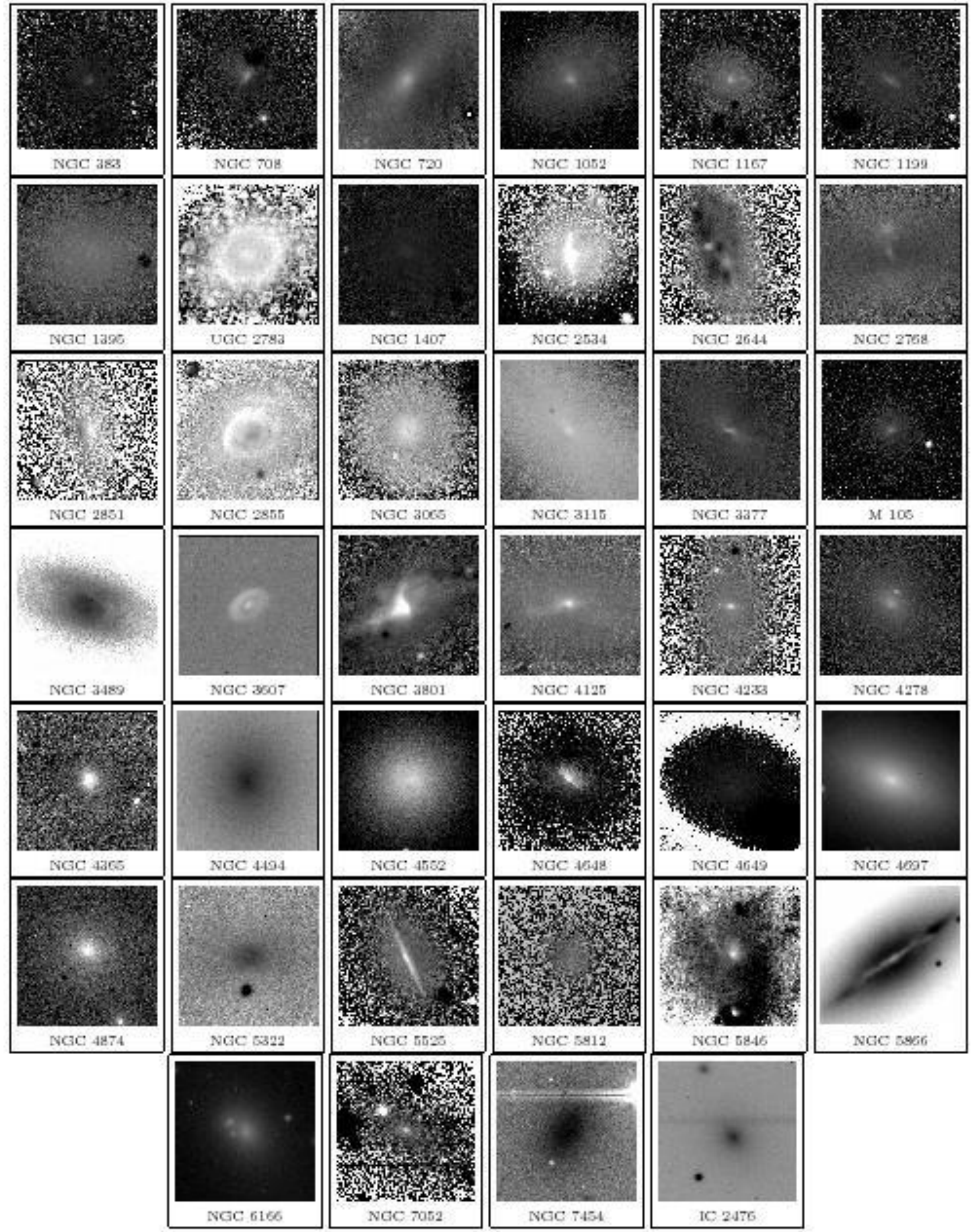
Sample Details

S.No.	Galaxy	RA(2000) hh:mm:ss	Dec(2000) dd:mm:ss	Type	Mag	Diameter (arcmin)	z	observed bands
01.	NGC0383	01:04:39	36:09:07	-3.0 (SA0-)	13.38	1.6x1.4	0.017000	B,V,R,I
02.	NGC0708	01:52:46	36:09:07	-5.0 (cD;E)	13.70	3.0x2.5	0.016195	B,V,R,I,H_{α}*
03.	NGC0720	01:53:00	-13:44:19	-5.0 (E5)	11.16	4.7x2.4	0.005821	B,V,R,I,H_{α}*
04.	NGC1052	02:41:04	-08:15:21	-5.0 E4	12.10	3.2x2.1	0.004900	B,V,R,I,H_{α}*
05.	NGC1167	03:01:42	35:12:21	-3.0 (SA0)	13.38	2.8x2.3	0.0614	B,V,R,I,H_{α}
06.	NGC1199	03:01:18	-15:48:29	-5.0 (E3)	12.37	2.4x1.9	0.008573	B,V,R,I,H_{α}*
07.	NGC1395	03:38:29	-23:01:40	-5.0 (E2)	10.97	5.9x4.5	0.005700	B,V,R,I,*
08.	UGC2783	03:34:18	39:21:25	-5.0 (S0)	12.99	1.3x1.2	0.022499	B,V,I,H_{α}
09.	NGC1407	03:40:11	-18:34:49	-5.0 (E0)	10.70	4.6x4.3	0.005934	B,V,R,I,H_{α}*
10.	NGC2534	08:12:54	55:40:19	-5.0 (E1)	13.70	1.4x1.2	0.01150	B,V,R,I,H_{α}*
11.	NGC2592	08:27:08	25:58:13	-5.0 (E)	13.28	1.7x1.4	0.006825	V,H_{α}
12.	NGC2644	08:41:31	04:58:49	S?	13.31	2.1x0.8	0.00647	B,V,R,I ,H_{α}*
13.	NGC2768	09:11:37	60:02:14	-5.0 (S0)	10.84	8.1x4.0	0.004580	B,V,R,I,H_{α}*
14.	NGC2851	09:20:30	-16:29:43	-2.0 (E)	15	1.2x0.5	0.017000	B,V,R,I
15.	NGC2855	09:21:27	-11:54:34	0.0 (SA)	12.63	2.5x2.2	0.00633	B,R,I,H_{α}*
16.	NGC3065	10:01:55	72:10:13	SA	13.5	1.7x1.7	0.00667	B,V,R,I
17.	NGC3115	10:05:14	-07:43:07	-3.0 (S0)	09.87	7.2x2.0	0.002402	B,V,R,I,H_{α}*
18.	NGC3377	10:47:42	13:59:08	-5.0 (E5-6)	11.24	5.2x3.0	0.002218	B,V,R,H_{α}*
19.	M 105	10:47:49	12:34:54	-5.0 (E1)	10.24	5.4x4.0	0.003039	B,V,R,H_{α}*
20.	NGC3489	11:00:18	13:54:04	-1.0 ()	11.12	3.5x2.0	0.002258	B,V,R,I,H_{α}
21.	NGC3607	11:16:54	18:03:07	-2.0(SA)	10.82	4.9x2.5	0.00312	B,V,R,H_{α}*
22.	NGC3801	11:40:16	17:43:41	-2.0 (S0/a)	12.96	3.5x2.1	0.011000	B,V,R,I,H_{α}*
23.	NGC4125	12:08:06	65:10:27	-5.0 (E6)	10.65	5.8x3.2	0.00452	B,V,*
24.	NGC4233	12:17:07	07:37:28	S0	12.8	2.3x0.9	0.0079	B,V,R,I
25.	NGC4278	12:20:06	29:16:51	-5.0 (E1)	11.20	4.1x3.8	0.002165	V,R,I
26.	NGC4365	12:24:28	07:19:03	-5.0 (E3)	10.52	6.9x5.0	0.004146	B,V,R,I,H_{α}*
27.	NGC4494	12:31:24	25:46:30	(E1)	10.71	4.8x3.0	0.0045	B,V,R,I,H_{α}
28.	NGC4552	12:35:39	12:33:23	E	10.73	5.1x4.7	0.001134	B,V
29.	NGC4648	12:41:44	74:25:15	-5.0 (E3)	12.96	2.1x1.6	0.004717	B,V,R,I
30.	NGC4649	12:43:39	11:33:09	-5.0 (E2)	09.81	7.4x6.0	0.003726	B,V,R,H_{α}*
31.	NGC4697	12:48:35	-05:48:02	-5.0 (E6)	10.10	7.2x4.7	0.00414	B,V,R,I,*
32.	NGC4874	12:59:35	27:57:34	-4.0 (cD)	12.63	1.9x1.9	0.024097	B,V,R,I
33.	NGC5322	13:49:15	60:11:26	-5.0 (E3-4)	11.14	5.9x3.9	0.00594	B,V,I,*
34.	NGC5525	14:15:39	14:16:57	S0	13.6	1.4x0.9	0.01852	B,V,R,H_{α}
35.	NGC5812	15:00:55	-07:27:26	-5.0 (E0)	12.19	2.1x1.9	0.006571	V,R,H_{α}
36.	NGC5846	15:06:29	01:36:20	-5.0 (E0-1)	11.05	4.1x3.8	0.00572	B,V,R,I,H_{α}
37.	NGC5866	15:06:29	55:45:48	-1.0 (S0)	10.74	4.7x1.9	0.00224	B,V,R,I,H_{α}*
38.	NGC6166	16:28:38	39:33:06	-4.0 (E2)	12.78	1.9x1.4	0.030354	B,V,R,I,H_{α}
39.	NGC7052	21:18:33	26:26:48	-5.0 (E)	13.40	2.5x1.4	0.015584	B,I,H_{α}
40.	NGC7454	23:01:07	16:22:58	(E4)	12.78	2.2x1.6	0.0067	B,V,R,H_{α}
41.	IC 2476*	09:27:52	29:59:09	S0	13.85	1.5x1.4	0.0269	B,V,R

Color -Map

- *Colour-map was prepared by dividing two images, widely separated in wave lengths, after matching their PSF, and converting it into the magnitude scale. Used for detection of dust features within the galaxy.*

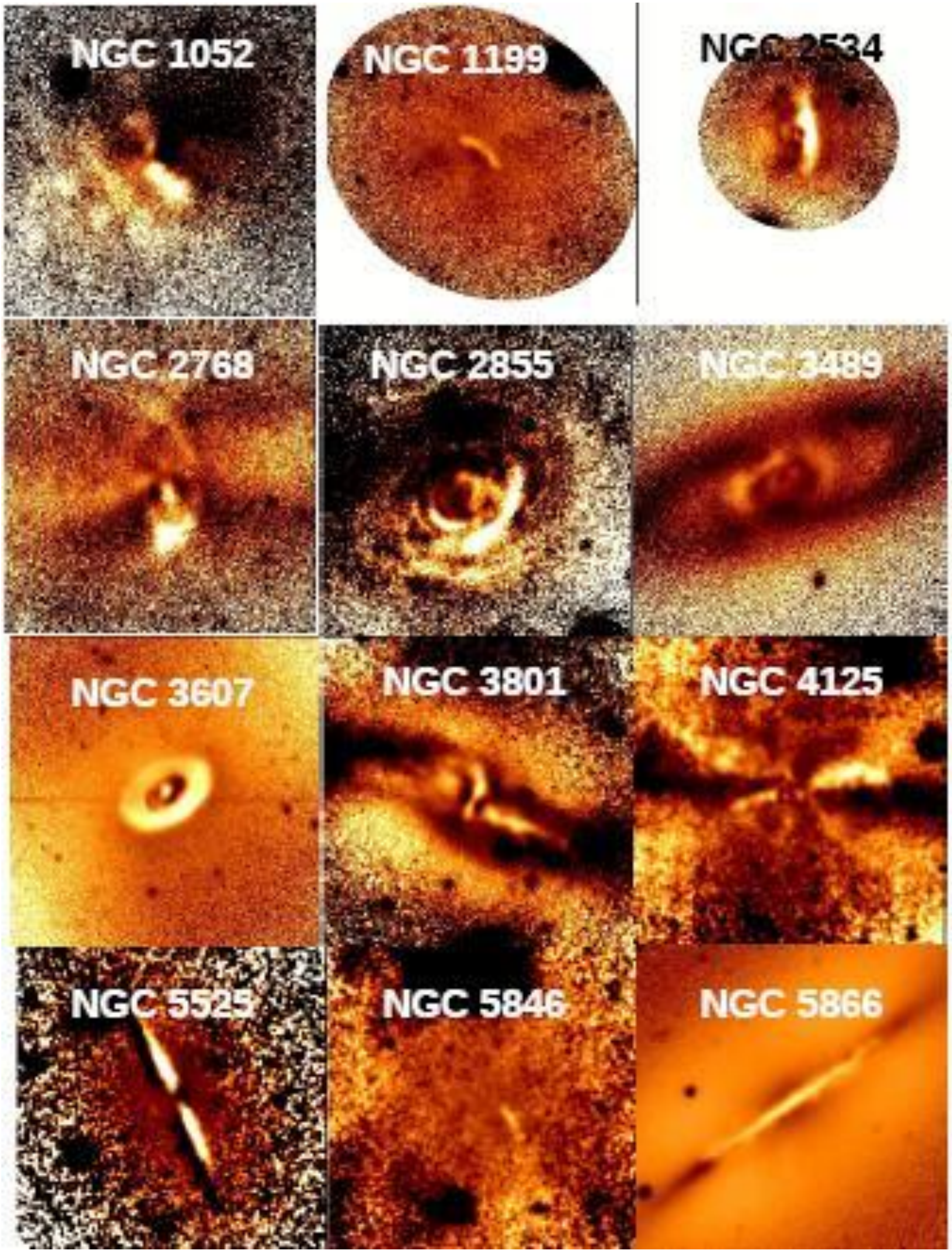
- *Most of the sample galaxies show presence of dust in a variety of morphology e,g lane or ring, nuclear dust or patches, whereas some of them consist of large complicated dust lanes or ring.*



Extinction Map:

The values of R_v, the ratio between the total extinction in V band and the selective extinction E(B-V) between B and V bands, for dust rich sample galaxies, lie in the range 2.05 - 3.84, with an average of 3.16±0.7

Galaxy Name	Total to Selective Extinction ratio			
	R_B	R_V	R_R	R_I
NGC 1052	3.9±0.3	2.9±0.5	1.9±0.2	1.5±0.3
NGC 1199	3.5±0.3	2.5±0.4	2.2±0.2	1.7±0.2
NGC 2534	3.05±0.1	2.05±0.2	2.02±0.1	1.08±0.1
NGC 2768	3.14±0.1	2.14±0.2	1.26±0.1	-
NGC 2855	4.16±0.2	3.16±0.3	2.36±0.1	1.98±0.2
NGC 3489	4.08±0.2	3.08±0.3	2.6±0.1	1.7±0.1
NGC 3607	3.26±0.7	2.26±0.7	1.88±0.6	--
NGC 3801	4.40±0.9	3.84±0.9	3.07±1.3	-
NGC 4125	4.65±0.2	3.65±0.2	3.06±0.2	-
NGC 5525	4.16±0.2	3.16±0.2	2.33±0.1	1.89±0.1
NGC 5846	4.4±0.2	3.4±0.4	2.4±0.3	-
NGC 5866	3.48±0.4	2.48±0.4	2.17±0.4	1.76±0.4



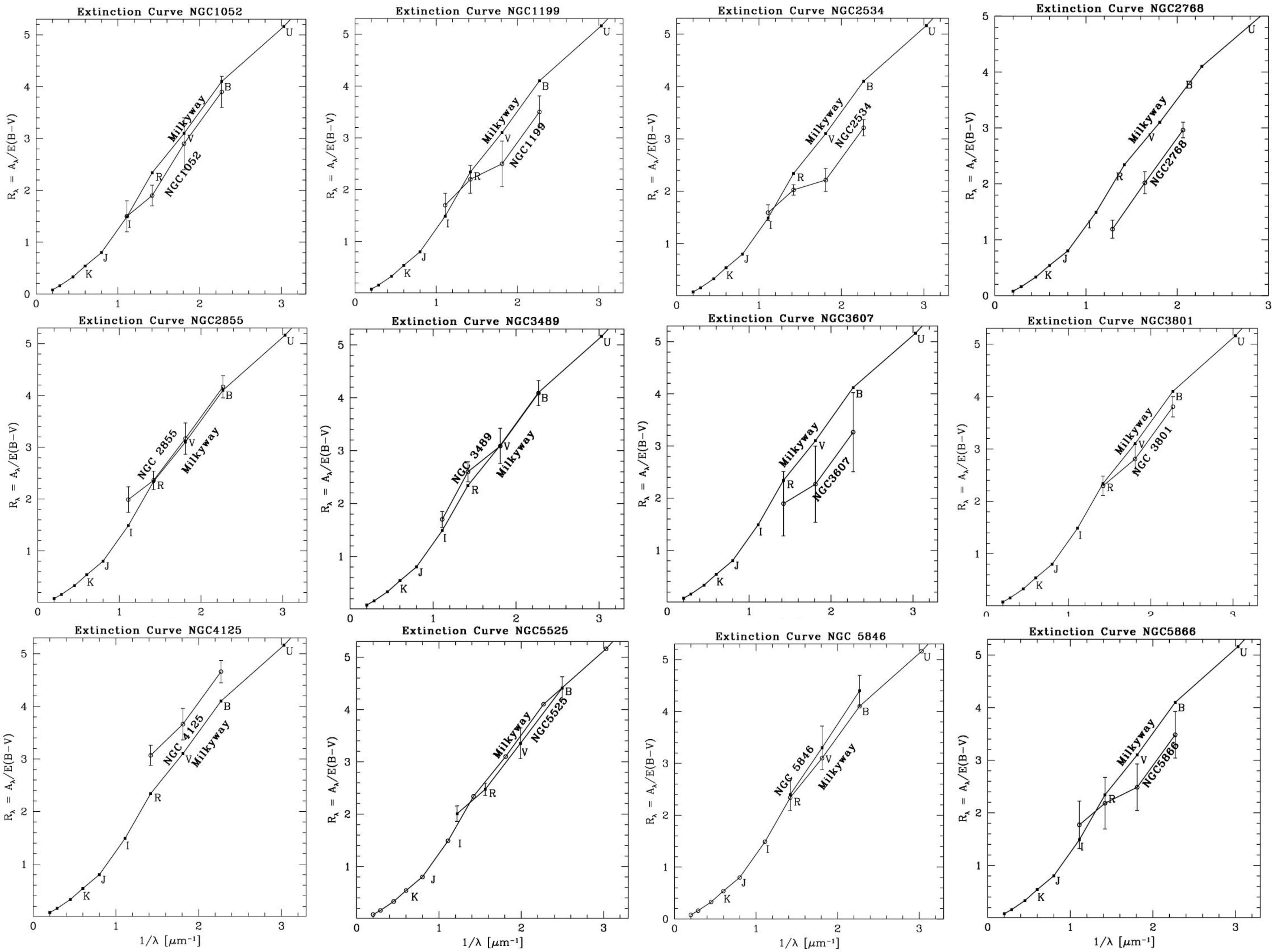
Extinction Curve

- *The extinction curves derived for the sample galaxies run parallel to that of canonical curve of our Galaxy, suggesting similar optical extinction properties of dust grains in extragalactic environment as that of the Milky Way.*

- *The observed deviation in the extinction value (at different bands) from the Milky Way values, is due to variation in the grain size.*

- *The relative size of the dust grains* $<a>/<a_{gal}>$ *in these galaxies is found to vary between 0.83 – 1.36*

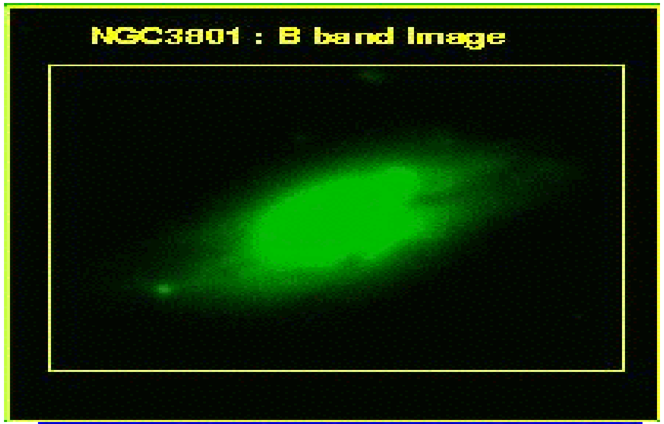
Galaxy Name	Relative Grain Size
NGC 1052	0.94
NGC 1199	0.93
NGC 2534	0.83
NGC 2768	0.75
NGC 2855	0.95
NGC 3489	1.04
NGC 3607	0.87
NGC 3801	1.47
NGC 4125	1.36
NGC 5525	1.01
NGC 5846	1.114
NGC 5866	0.98


Extinction Curve NGC1052
Extinction Curve NGC1199
Extinction Curve NGC2534
Extinction Curve NGC2768
Extinction Curve NGC2855
Extinction Curve NGC3489
Extinction Curve NGC3607
Extinction Curve NGC3801
Extinction Curve NGC4125
Extinction Curve NGC5525
Extinction Curve NGC 5846
Extinction Curve NGC5866
Milkyway
NGC1052
NGC1199
NGC2534
NGC2768
NGC 2855
NGC 3489
NGC3607
NGC 3801
NGC 4125
NGC5525
NGC 5846
NGC5866
U
B
V
R
I
J
K
$R_\lambda = A_\lambda/E(B-V)$
$1/\lambda$ [μm^{-1}]

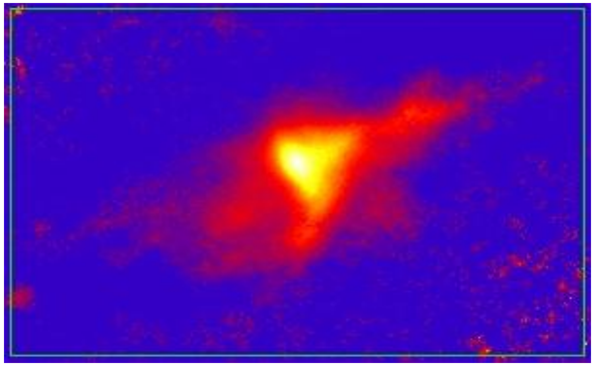
Comparison with the other phases of ISM

Dust and ionized gas in NGC 3801

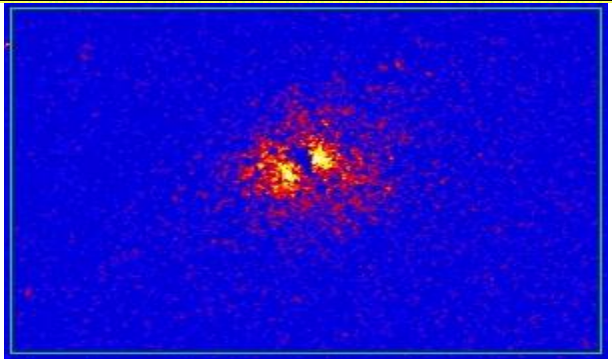
The Figures show B-R color index map and an Hα+[NII] emission-line image with the continuum subtracted and the contour of Hα overlaid on the B-R color map. Images are on the same scale. North is down and east is to the right.



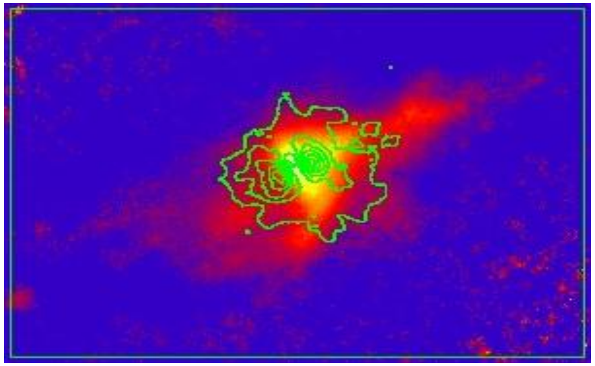
Imaged with HCT



B-R color map



Hα emission map

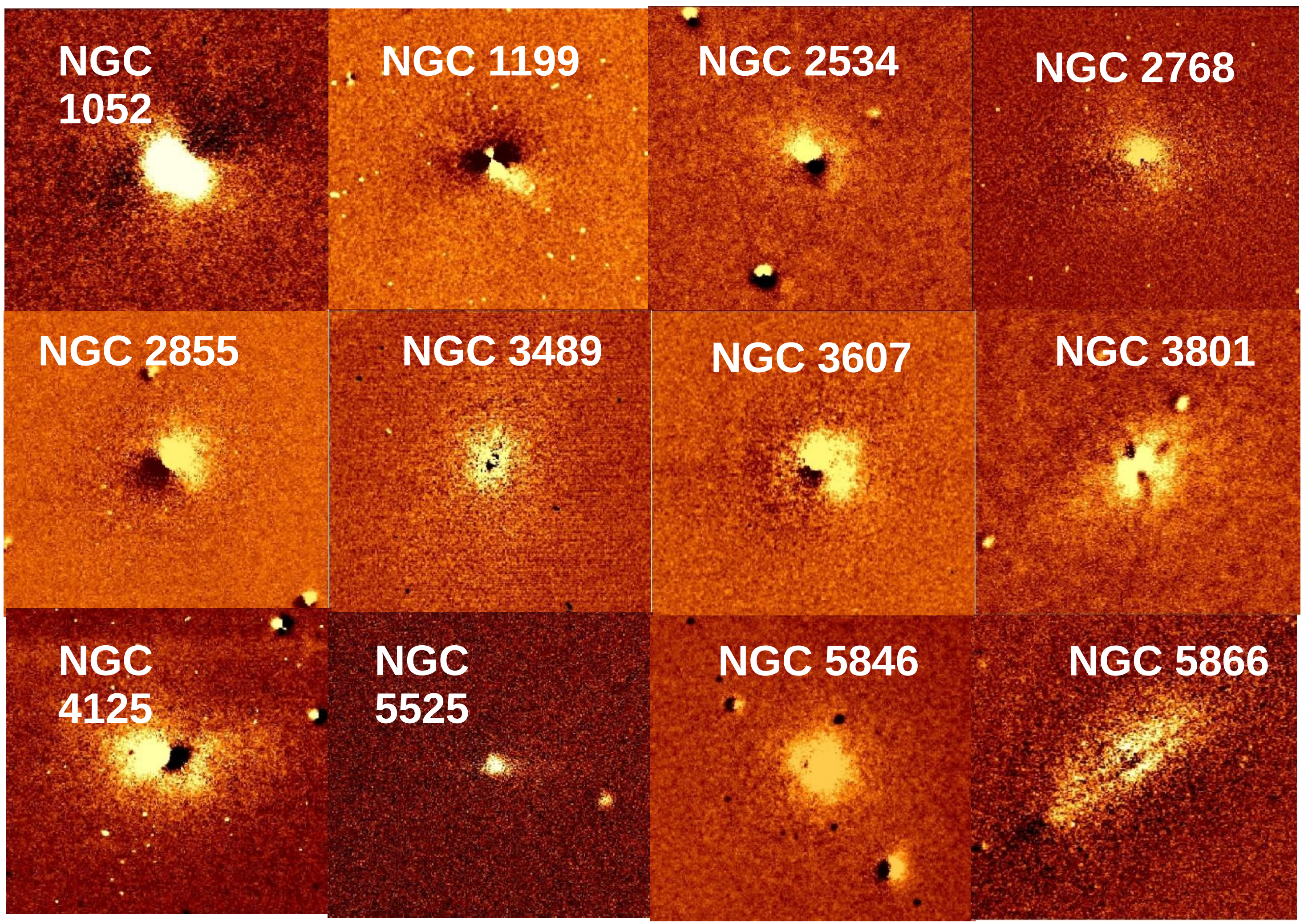


Hα-contours

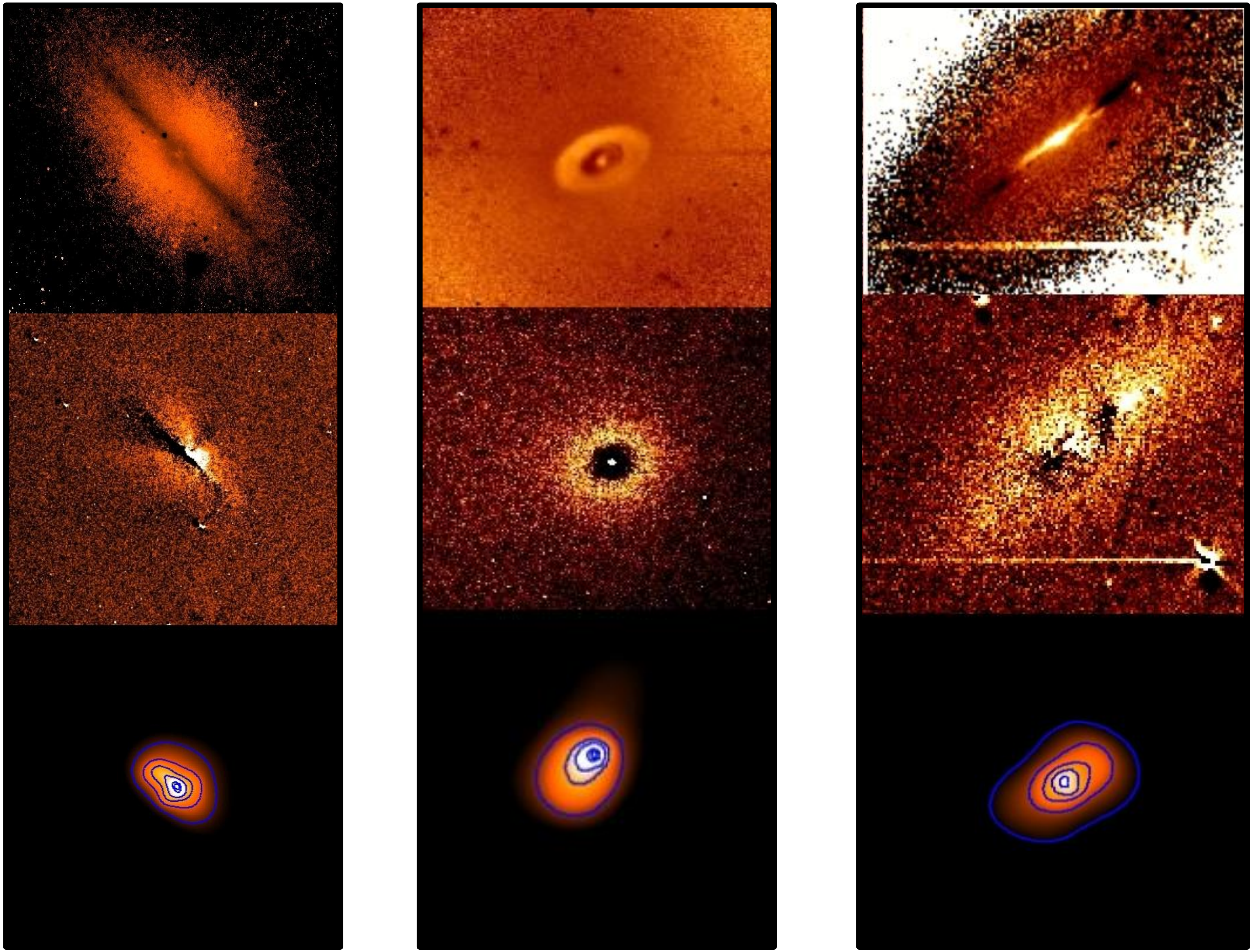
Chaware et al. 2005, BASI 33, 401

Comparison with the other phases of ISM

H-alpha Emission Map : *H-alpha emission was obtained by subtracting the continuum.*



Dust, ionized gas and hot gas morphologies



Morphologies of dust (upper panel), Hα+[N II] emission regions (middle panel) and diffuse X-ray emission maps (lower panel) for the galaxies NGC 3115, NGC 3607 and NGC 5866, respectively.

Comparison with the other phases of ISM

- *From H-alpha emission map and using the spectrophotometric standards we calculate the H-alpha flux.*

- *H-alpha flux from the emission map was then used to calculate the Star Formation Rate (SFR), following the procedure described by Kennicutt (1998).*

$$SFR(M_o\, yr^{-1}) = 7.9 \times 10^{-42} \times L_{halpha}$$

- *SFR was also calculated for IRAS (FIR) flux at 60μm and 100μm and compared (Young 1989). Mass Loss Rate is also calculated.*

- *Dust mass was calculated in optical band using the relative grain size obtained from the extinction curve, whereas in Far Infrared we used IRAS flux at 60 and 100 μm.*

- *IRAS flux also gives an estimate of dust temperature.*

- *Diffuse X-ray emission maps in different energy bands, soft (0.3-1keV) and hard (2-10 keV) were derived using adaptive filter "csmooth", in order to compare and contrast the morphology of hot gas with that of dust and ionized gas.*

Results

- **Galaxies with well settled dust lanes have their R_v significantly smaller than the canonical value 3.1, while others have slightly larger R_v values.**

- ***Mass of dust calculated using the total optical extinction is in the range 10^3 to 10^6 M_{SUN}, an order of magnitude lower than those estimated using IRAS flux. This indicates that a fraction of dust is diffusely distributed, throughout the galaxy and could not be detected through optical observations in agreement with Patil et al. (2007), Finkelman et al (2010)***

- ***The morphology of dust, ionized gas and X-ray emission for these galaxies are found to be similar, implying their physical association. Various ionization mechanism have been proposed (Finkelman et al. 2010), Star formation at a low level in these galaxies could be a major source of ionization.***

- ***Star formation rate was estimated using H_α as well as IRAS flux, to look for association of SFR with the presence of dust and gas. SFR ranges from 0.02-0.12 $M_{SUN} yr^{-1}$ which lies within the range of SFR given by Thronson & Bally (1987) for early type galaxies.***

Results

Galaxy Name	Optical Dust Mass (log $M_\odot$)	Dust Mass using IRAS flux (log $M_\odot$)	Dust Temp	SFR using Halpha flux ($M_\odot yr^{-1}$)	SFR using IRAS flux ($M_\odot yr^{-1}$)	Mass Loss Rate($M_\odot yr^{-1}$)
NGC 1052	2.14	5.2	38.7K	0.10	0.09	0.05
NGC 1199	2.21	< 4.56	35.7K	0.10	0.011	0.01
NGC 2534	3.31	5.69	34 K	0.12	0.19	0.04
NGC 2768	2.67	5.36	29 K	0.03	-	-
NGC 2855	3.21	6.17	26 K	0.08	0.06	0.04
NGC 3489	2.35	5.69	33 K	0.02	NA	NA
NGC 3607	2.12	NA	NA	0.03	NA	NA
NGC 3801	6.41	8.25	NA	0.12	0.05	0.08
NGC 4125	2.61	5.14	34 K	0.14	0.06	0.01
NGC 5525	5.05	NA	NA	0.0	NA	NA
NGC 5846	3.11	< 4.53	29.5K	0.004	0.003	0.01
NGC 5866	3.00	5.92	29.08K	0.05	<0.2	0.14

Origin of dust: *Internal Vs. External*

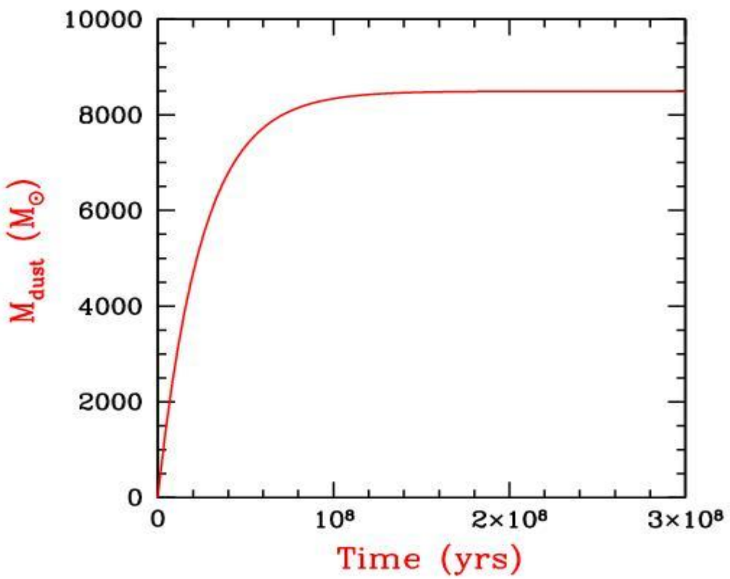
1. Internal sources: mass-loss from the evolved stars

- Present day mass-loss rate

$\dot{M} = 10^{-6} D^2 (S_{12} - 0.042\, S_{100})$ **$M_\odot$/yr**

- This is simultaneously destroyed in presence of hot gas i.e. X-ray with a life-time of grains ~ $10^6 - 10^7$ yr (Draine & Salpepter 1979)

Fig: NGC 4370 – Dust mass accumulation



⇨ **Accumulated dust 100 times smaller than the observed dust**

⇨ **It is surprising to find dust existing over the Hubble time despite its destruction time scale is 10^6-10^7 yrs**

Origin of dust ....

2.External sources: direct merger, accretion or tidal capture

Arguments in favor of external origin:

- **No reason why internally produced dust will tend to line up as a well ordered lane rather than sinking in the potential well of the galaxy**

- **Kinematics of the gas associated with dust lanes often differs from that of stars**

=>**Material present in the lanes accreted from outside the galaxy**
(Sharples et al. 1983; Schweitzer 1983)

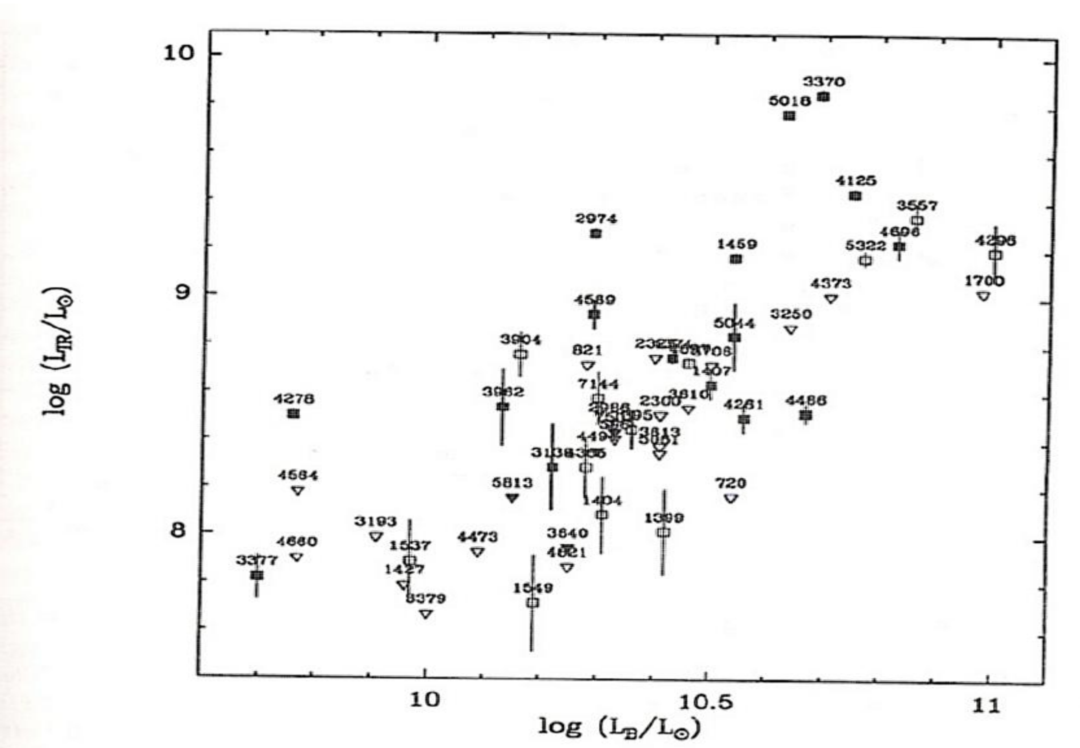
- **Spatial correspondence of dust with ionized and hot gas (Multi-phase ISM) in these galaxies is surprising**

=> de Jong et al.(1990) proposed "***evaporation flow***" scenario ------ cool clouds of gas & dust accreted during a merging collision with a gas-rich companion galaxy are heated and evaporated by thermal conduction in the X-ray plasma locally cooling the hot gas

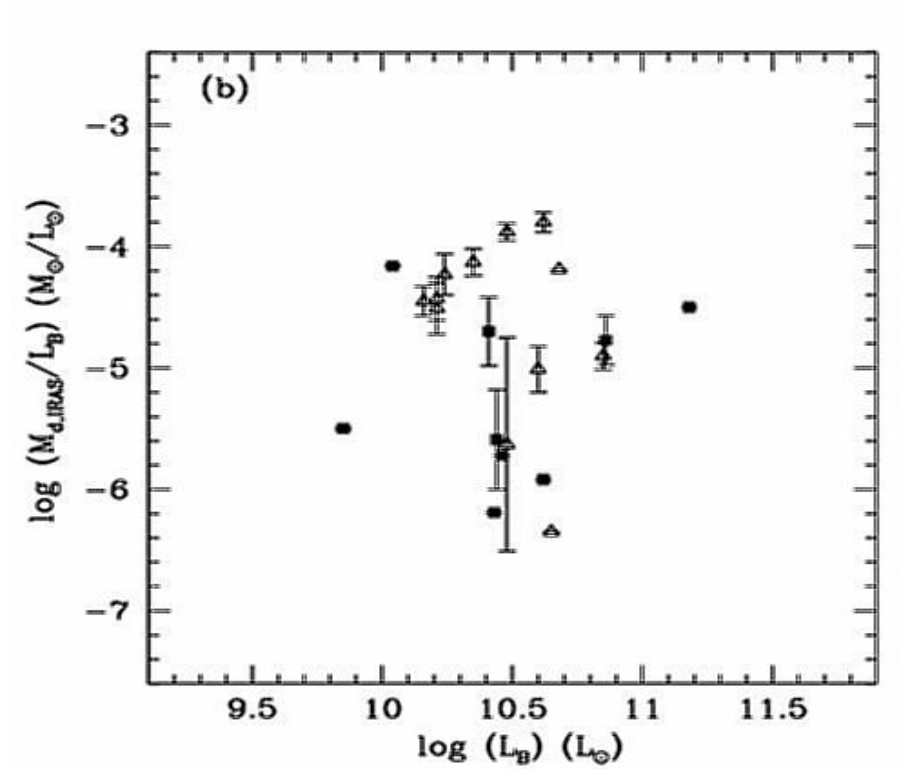
Origin of dust ….

In favour of external origin:

Another good argument in favour of external, merger-related origin is the lack of significant correlation between the L_{FIR} ($M_{d,IRAS}$) vs. L_B



(Goudfrooij et al. 1994b)



(Patil et al. 2007)

Thank you