Dust and Multiphase ISM in Early type Galaxies

NGC 5846; Multiphase ISM and their possible physical association (X-ray, ionized gas & dust)
Goodfrooj & Trenchieri (1998)

S K Pandey (proskp@gmail.com)
Pt Ravishankar Shukla University, Raipur, Chhattisgarh, India
www.prsu.ac.in
Galaxies: an overview

- Galaxies are massive, gravitationally bound systems consisting of stars, stellar remnants and interstellar medium of gas and dust.
- Galaxy morphology is still a logical starting point for understanding galaxies.

Hubble’s Galaxy Classification Scheme

**Early-type**
- Elliptical galaxies - ellipse-shaped light profile.
- Lenticular galaxies - central bulge and a surrounding disk.

**Late-type**
- Spiral galaxies - disk-shaped with dusty, curving arms.
- Irregular galaxies - unusual shapes
Early-type Galaxies

Text Book scenario….  

- No striking features ("simply ball of light", no axis of rotation)  
- Light is exclusively from stars  
- Only “old” stars, almost no gas and dust  
- Optically yellowish-red  
- “Red and dead” No signs Star Formation  
- “Really very boring
Early-type Galaxies

Present scenario....

- 90% ETGs rotate!
  (e.g. Emsellem et al. 2011)

- ~90% have imbedded stellar disks
  (Krajnovic et al. 2013)

- Nearly all galaxies host complex ISM

- Ongoing Star Formation

- “Really very interesting”
Nearly all ETGS are detected in X-rays

~70% ETGs host ionized gas disks

~40% ETGs host HI reservoirs

~23% ETGs host Molecular gas

All the known phases of ISM have been detected in ETGs

~70% ETGs host dust

(Patil, Pandey et al 2007)

Patil, Pandey et al 2007

~40% ETGs host HI reservoirs

(Patil, Pandey et al 2007)

(Patil, Pandey et al 2007)

(Patil et al. 2001)
## Phases of the ISM

<table>
<thead>
<tr>
<th>Constituents of ISM</th>
<th>Temperature</th>
<th>Mode of detection</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>atomic hydrogen HI</td>
<td>50...300K</td>
<td>21cm radio line</td>
<td>External</td>
</tr>
<tr>
<td></td>
<td>1...100 cm(^{-3})</td>
<td>UV absorption lines</td>
<td></td>
</tr>
<tr>
<td>molecular hydrogen H(_2)</td>
<td>3...100K</td>
<td>UV absorption lines</td>
<td>External</td>
</tr>
<tr>
<td></td>
<td>10(^2)...10(^6) cm(^{-3})</td>
<td>IR emission lines</td>
<td></td>
</tr>
<tr>
<td>other molecules CO, HCN, H(_2)O ...</td>
<td>3...100K</td>
<td>radio and IR emission</td>
<td>External</td>
</tr>
<tr>
<td></td>
<td>10(^2)...10(^6) cm(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ionized hydrogen HIII</td>
<td>5000...10000K</td>
<td>optical and IR emission lines, radio continuum</td>
<td>External</td>
</tr>
<tr>
<td></td>
<td>10(^2)...10(^4) cm(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hot gas</td>
<td>10(^6)...10(^7)K</td>
<td>X-ray emission</td>
<td>Internal</td>
</tr>
<tr>
<td></td>
<td>0.01 cm(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dust grains</td>
<td>20...100K</td>
<td>reddening/absorption of starlight, IR emission</td>
<td>External</td>
</tr>
<tr>
<td></td>
<td>size (\approx) 2000\AA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>magnetic fields</td>
<td>(\mu)Gauss</td>
<td>polarization of stars, Zeeman effect, synchrotron radiation</td>
<td>Internal</td>
</tr>
<tr>
<td>cosmic rays</td>
<td>energies up to 10(^{20}) eV</td>
<td>air showers</td>
<td>Internal</td>
</tr>
</tbody>
</table>
Inter Stellar Matter (ISM) in E/S0s

It is now well established that Es / S0s host all the known phases of ISM

- **Hot Gas**
  \[ T \sim 10^7 \text{ K} \]
  detected in 70% of E/SO
  Mass \(10^9 - 10^{11} \, M_\odot\)

- **Ionized Gas**
  \[ T \sim 10^4 \text{ K} \]
  detected in 70% of E/SO
  Mass \(10^3 - 10^5 \, M_\odot\)

- **Cool Gas (HI) and Molecular Gas (CO)**
  \[ T \leq 10 \text{ K}, \]
  detected in 8-10% of E/SO
  Mass \(\leq 10^7 \, M_\odot\)

- **Dust**
  \[ T \sim 10 - 100 \text{ K} \]
  detected in 50% of E/SO
  Mass \(10^4 - 10^7 \, M_\odot\)

*Except Hot gas, origin of other phases of ISM is external*
Interstellar Extinction Law
The Dust

1. Dust is ubiquitous, in different environments including galaxies, quasars, AGNs etc.
2. Dust grains extinguishes light at UV and optical wave lengths and re-emits at IR wave lengths
   =>wavelength dependent, selective extinction
3. 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 Å° to a few µm.
4. Dust is an important component of ISM in early type galaxies
Why dust?

i.e. objectives

- Investigate the wavelength dependent dust extinction and compare with that of the dust in our Galaxy.

- Examine the relationship of the dust with the different phases of the ISM.

  Available only for only a handful of ellipticals and lenticulars

Clearly, there is a need to extend this work to a large sample of E/SOs.

→ expected to provide a better understanding of the nature, origin and evolution of ISM in early-type galaxies.
Detection of Dust: Optical vs. Far-IR

Infra-red data:
- As dust opacity is low in IR, detection is not hampered by orientation effects
  
  IRAS flux densities provides better estimates of dust content

- Disadvantages:
  - less sensitive than optical as the IR emission is fairly weak

Optical data:

Owing to their higher spatial resolution, optical CCD imaging is essential in establishing the presence & distribution of dust

Helps to measure reddening and hence the dust extinction properties

- Disadvantages:
  - Sensitive to geometry i.e. edge on disks easily seen while face on disk difficult
  - Always provides a lower limit for the dust content
Detection of dust

Visual inspection:

NGC 2907
NGC 3665
NGC 7722
NGC 5485
NGC 5363
NGC 4370
Dust has been detected in majority of E/So galaxies.

Dust appears in a variety of forms e.g. lanes, rings, and filaments, patches etc.
Dust: few more cases...

NGC 2907

NGC 3665

NGC 5485

NGC 7722

NGC 5363

NGC 4370

(Patil, Pandey, Kembhavi 2007)
Dust: few more cases...

NGC 2907
NGC 3665
NGC 5363
NGC 7722
NGC 4389
NGC 4370

(Patil, Pandey, Kembhavi 2007)
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 = $E(B-V) = A_B - A_V$

=> Works well if individual stars are resolved and sufficiently bright over a wide range of wavelength for the determination of $A_\lambda$ as a function of $\lambda$. (Milky Way, SMC, LMC)
• For the Milky way one finds that
  (i) The extinction curve varies linearly with $\lambda^{-1}$ 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.

$\Rightarrow R_v = 3.1$ (Milky way), 2.7(SMC), 3.2(LMC)
Dust : extinction

Indirect Method:

- Comparison of actual observed light distribution from a galaxy with that expected in the absence of dust, as a function of $\lambda$ will provide an estimate $A_{\lambda}$.

- Early-type galaxies are suitable targets owing to their inherently smooth distribution of light.
Dust Extinction

• Extinction maps:
  Quantitative measure of the dust extinction

\[ A_\lambda = -2.5 \log \left( \frac{I_{\lambda,\text{obs}}}{I_{\lambda,\text{model}}} \right) \]

Here, \( I_{\lambda,\text{model}} \)
→ from ellipse fitting

Example→
Dust in early-type galaxies (Es and S0s)

Galaxy Pair Method:

Original

Dust free model

(Patil, Pandey, Kembhavi et al. 2007)
Dust and isophote distortion

Color-index map of NGC2534
Extinction Maps:  
(Dust morphology)

- Dust morphology was further confirmed by their extinction maps

- These were used to derive wavelength dependent of the dust extinction

(Kulkarni et al, 2014)
Extinction curves:

- $R_{\lambda}$ varies with inverse wavelength
- In most of the cases "curve" is parallel to the Galactic curve

Grains in extragalactic environment are identical to canonical grains

Assuming similar chemical composition and MRN model, dust extinction can be quantified as:

$$A_{\lambda} = 1.086 N_d \pi a^2 Q_{ext}$$
Dust in early-type galaxies: Extinction Curve

(Patil, Pandey, Kembhavi et al. 2007)
Dust Using SALT

Finkelman et al. 2008

CCD imaging observations extending to UV obtained during performance Verification phase for 9 ellipticals.
Dust With SALT

Extinction curves run parallel to the canonical Galactic curve. $R_V = 2.82 \pm 0.38$, indicating that characteristic grain size is smaller than that in the Milky Way; confirm results of Patil et al. 2007.
Dust Mass:

Dust mass from optical extinction:

\[ M_d = \int_{a_{\text{min}}}^{a_{\text{max}}} \frac{4}{3} \rho_d n(a) da \times l_d \times \text{Area} \]

Far-IR data (IRAS) flux densities:

Using single temperature model emitting at IR wavelengths

\[ M_{d,\text{IRAS}} = \frac{4}{3} \alpha \rho_d D^2 \frac{F_v}{Q_v B_v(T_d)}, \quad \text{where} \quad T_d = 40 \left( \frac{S_{60}}{S_{100}} \right)^{0.4} \]
Comparison of the dust mass estimates from optical extinction and IRAS flux densities:

- Dust mass from FIR data roughly two order of magnitudes higher compared to estimates from optical data

A large fraction of dust has diffuse distribution throughout the galaxy

(Kulkarni et al. 2014)
Hot X-ray emitting gas

- Space borne X-ray observatories: from Einstein to ROSAT, ASCA, CHANDRA, XMM …..
- A large population of E/SOs detected in X-rays
- Two components:
  1. Discrete arising mostly from LMXB,
  2. Diffuse emission from hot thermal plasma
Morphology of hot gas in early-type galaxies:

Morphology of X-ray emission can provide the important clues into the nature of hot gas

(Vagshette, Patil et al. 2013)
Dichotomy in X-ray morphology (Field vs. group/cluster)

X-ray emission from clusters exhibit sharp peak against the field galaxies

(Vagshette, Patil et al. 2013)
Hot gas in ETGs:

NGC 4365

Notice the contribution from discrete sources

X-ray emission from ETGs have additional component from XRBs, like those seen in spirals
The relation between X-ray luminosity ($L_X$) and optical luminosity ($L_B$) is studied, with bright galaxies typically gas dominated and faint galaxies typically LMXB dominated. The relation is given by $L_X \propto L_B^{1.7-3.0}$, with a dispersion of approximately 50-100.

Key references include:

- Trinchieri & Fabbiano 1985
- Brown & Bregman 1998
- Irwin & Sarazin 1998
- Beuing et al. 1999
- O'Sullivan et al. 2001
X-ray Pont sources have also been found in dusty early-type galaxies:

GG – red cross; GC - blue-violet filled circle; BCG - magenta open circle; FG - gold pentagon.

Red – lenticular galaxies and gold – elliptical galaxies

(Vagshette, Patil et al. 2012)
Ionized Gas

- ~55-60% of E/SO contain warm gas
- Temp ~10(^4) K,
- Mass ~10(^2) -10(^7) Msun
- A variety of morphologies
- Sources of ionization:
  - AGN,
  - Interaction with hot ISM
  - Hot young stars
  - pAGB stars
  - Star formation
**Hα emission maps**

- IRAF was used for the preliminary data reduction.
- **Hα** emission map was obtained by subtracting the scaled continuum from the Hα frames.
- Galaxies with presence of line emission (Kulkarni, 2014)

Size of the image cutouts
90 arcsec x 90 arcsec
Cold phase of ISM in ETGs: **CARMA** Survey

CARMA - Combined Array for Research in Millimeter-wave Astronomy

Fig. CO detections (blue) overlaid on optical images. A Variety of morphological features are evident.

(Davis et al. 2011, Alatalo et al. 2013)
Dust with Atomic and Molecular gas:

- **UGC 1503**
- **NGC 807**
- **NGC 3656**

Fig. Optical, IR, CO and HI morphologies (Young et al. 2013)
CO: Morphology (CARMA):

- H$_2$ and stars often misaligned: 
  > 35% external origin (mostly field)
  < 65% internal origin (clusters/groups)

- H$_2$ and ionised gas always aligned: common origin

(Alatalo et al. 2012; Davis et al. 2012)
Multiphase ISM in galaxies:

Dust + warm gas

Dust + warm gas + hot gas

(Patil et al. 2007)
Multiphase ISM in NGC 1482

(Vagshette, Pandey, Patil, 2012)
Multiphase ISM in NGC 1316

(Deshmukh, Pandey, Patil 2013)
Dust, Ionized, Hot, Atomic gas (Multiphase ISM) in M 86

Stars in r band
Hot gas in X-rays

Cold dust emission at 250 and 500 µm

HI emission at 21 cm
Ionized gas in Hα

(Kenney et al. 2008)

(Alighieri et al. 2013)
Dust obscuration vs emission: NGC 5485

SDSS g band vs Herschel IR (100, 160 and 250 μm) data.

Beam FWHM for Herschel data is shown in figure.

(Baes et al. 2014)
NGC 5128: A classical case

Temperature map & total gas mass distribution

(Parkin et al. 2012)
Origin of the dust:
Mass Buildup - Mass Loss From Evolved Stars

\[
\frac{\partial M_d(t)}{\partial t} = \frac{\partial M_d,s}{\partial t} - M_d(t) t_d^{-1}
\]

Stellar mass loss not enough, origin of dust is therefore external to the galaxy.

(Patil, Pandey, et al. 2007)
Luminous galaxies is expected to contain large amount of dust.

However, a weak anti-correlation between the two hints towards external origin of dust.
A weak correlation between $L_B$ vs $L_{\text{H}\alpha}$ indicates that main source of gas ionization is non-stellar. But a strong correlation between $L_{\text{FIR}}$ vs $L_{\text{H}\alpha}$ points to their common origin. Optically bright galaxies contain more stars, hence more possibility of ionization of gas. But Halpha flux is not correlating well. It is correlated well with IR flux implying that they must be associated with one another.
Fig. Correlation between the FIR vs. 1.4 GHz radio continuum for ETGs (black). Red points represent disk galaxies from UGC catalogue (21cm emitting atomic gas also shows good correlation with FIR flux and its distribution is almost similar to disk galaxies. Same was demonstrated in CO detections also)
FIR line ratios in ETGs are almost similar to those in spirals; detection of atomic at other wave lengths are similar to spirals. (Lapham, Young et al. 2014)
Finkelman et al (2012) found a strong correlation (0.8) between HII mass and the dust mass for dust lane ETGs. For the combined sample (including Kulkarni, 2014) this reduces to 0.6 for all dusty ETGSs. A good correlation between warm gas and dust hint toward their common origin, mostly external.
A weak correlation (0.07) between $SFR_{FIR}$ & $SFR_{H\alpha}$ suggests that the FIR emission possibly results from the same young stellar population that produces $H\alpha$ emission.

This gets improved (0.9) if one takes Es with detected CO emission, as independent tracer of star formation (enlarged circles)

=> this indicates that newly formed stars could be common source for H-alpha as well as FIR in ETGs with CO emission.

(Kulkarni, 2014)
Star formation rates in ETGs are quite similar to spirals i.e. the data cannot be used to discriminate ETGs from Spirals! (Davis et al. 2014), ATLAS project
Thank you very much