The Galactic Matter Cycle and Star Formation

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The Galaxy

Dark clouds in front of the Galactic Center

from wikipedia – Milky Way
A small dark nebula: Barnard 68

Looking through an isolated dense core in the near infrared.

Pre-Collapse Black Cloud B68 (comparison)
(VLT ANTV + FORS 1 - NTT + SOFI)

ESO PR Photo 02c/01 (10 January 2001)
The constellation Orion harbors many bright and dark nebulae.

They are another telltale sign for matter between the stars.

But the whole picture emerges at far infrared wavelengths . . .
Orion in the Far Infrared
A few facts:

- The space between the stars is filled with gas and dust.
- The average density is one atom per cm$^3$. In this room, there are $6 \cdot 10^{19}$ atoms per cm$^3$.
- The average temperature is a few 1000 Kelvin (similar to stellar surfaces). But the temperature ranges from a few million Kelvin down to 10 Kelvin.
- The gas can be ionized (H$^+$), neutral (H), or molecular (H$_2$) depending on the temperature.
- About one percent in mass of the ISM are very fine ($\sim 1\mu m$) dust grains. The composition is similar to sand and soot.
- This little amount of dust is very important for the optical and chemical properties of the ISM.
Question?

Where does the gas and dust come from?

- Stars fuse hydrogen and helium into heavier elements, but how do these elements end up between the stars.
The Galactic Matter Cycle

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- But where do stars come from?
- Let’s look at the Galactic Matter Cycle...
The Galactic Matter Cycle

Stellar and interstellar Matter get recycled


Left: low-mass/sun-like stars – planetary nebulae
Right: high-mass stars – supernovae
In a few billion years, the sun's core will run out of hydrogen. The nuclear fire will continue to burn in a shell causing the sun to swell enormously. The outer layers will be blown into space.
Dying Low-Mass Stars

The Next Stage: a Proto-Planetary Nebula

Here, a sun-like star illuminates the shedded outer layers as it contracts and heats up. It will become a Planetary Nebula.

Proto-Planetary Nebula • Red Rectangle • HD 44179

HST • WFPC2

NASA, ESA, H. Van Winckel (Catholic University of Leuven) and M. Cohen (University of California, Berkeley)
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ISM
Galactic Matter Cycle
Dying Stars

low-mass
high-mass
Summary

Star Formation
Summary

Planetary Nebula NGC 2440

*Hubble Space Telescope* • WFPC2

NASA, ESA, and K. Noll (STScI)

STScI-PRC07-09
Planetary Nebulae Gallery

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Planetary Nebula M2-9
PRC97-38a • ST ScI OPO • December 17, 1997
B. Balick (University of Washington) and NASA
Dying High-Mass Stars

η Carinae,

This very massive star (100 $M_\odot$) is running out of hydrogen and starts to fuse heavier elements.

It burns in many shells violently bursting off its outer layers.

And the end is also much more violently...
Supernovae
Supernovae Remnants
Supernovae Remnants
Supernovae Remnants
Dying stars replenish the interstellar medium with gas and dust.
Massive stars enrich it with heavy elements.

http://chandra.harvard.edu/edu/edu/formal/stellar_ev/
Question?

What happens to the gas and dust?

Gravity

- Under its own gravity, the gas and dust concentrates in clouds.
- The gas cools and becomes molecular.
- More cooling by dust and molecular radiation allows the gas to collapse more and more.
- Stars form in the densest cloud cores.
How to form a low-mass star?

Dense cores in molecular cloud

Gravitational collapse

Design: Michiel Hogerheijde (nach Shu, Adams & Lizano 1987, ARAA 25, 23)
How to form a low-mass star?

Embedded protostar
Accretion, Jet, Outflow

Pre–main sequence star
Jet, Outflow

Design: Michiel Hogerheijde (nach Shu, Adams & Lizano 1987, ARAA 25, 23)
How to form a low-mass star?

Pre–main sequence star
Planet formation in disk

Main sequence star
with planetary system

Design: Michiel Hogerheijde (nach Shu, Adams & Lizano 1987, ARAA 25, 23)
Disks around Young Stars

Young Stellar Disks in Infrared

CoKu Tau1  DG Tau B  Haro 6-5B
IRAS 04016+2610  IRAS 04248+2612  IRAS 04302+2247

500 AU

PRC99-05a • STScI OPO
D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA
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Disks launch Jets

Jets from Young Stars
PRC95-24a · ST Scl OPO · June 6, 1995
C. Burrows (ST Scl), J. Hester (AZ State U.), J. Morse (ST Scl), NASA

scale bar = 1000 AU
Star formation is very inefficient. Only a few percent of the gas in a molecular cloud is converted into stars and planets.

The forming stars radiate energy gained mainly from contraction.

They are contracting till their central temperature reaches 10,000,000 K.

Then hydrogen fusion starts and a normal, a main-sequence star star is born.

The cycle is closed.
The space between the stars is filled with gas and dust: the Interstellar Medium or ISM.

The ISM can be studied at other wavelengths than the visible light.

The life of stars cycles matter in and out of the ISM.

Dying stars inject a (large) fraction of their mass into the ISM.

Massive stars enrich the ISM with heavy elements.

In the densest molecular clouds, a few percent of the ISM gets transformed into stars and planets.

We are all made of star dust!

Then jets, outflows, and supernovae disperse the cloud.
What is more: Massive Star Cluster

We further know:

All stars form in clusters.

While the sun formed a Supernova went off close by – $< 1.6 \text{ pc}$ away. (Looney at al. 2006)

The Sun forming close to massive stars is likely, but makes things complicated.

Nebula
Strong stellar winds erode the molecular cloud the massive star formed from and other dense cores around it.
Simulation of a Turbulent Cloud Collapsing

Mass $50 M_\odot$
Size 0.3 pc
Duration 266,000 yr

Forms 50 stars and Brown Dwarfs

100,000 CPU hours on up to 64 processors. In total $10^{16}$ FLOP.

Matthew Bate, University of Exeter (2002)