Astro 501: Radiative Processes
Lecture 39: The Final Frontier
May 1, 2013

Announcements:

- **Problem Set 11** due 5pm today
- **Final Exam**
  will consist of 24 hour, take-home problem set
  to be done without collaboration
  Assigned: Mon May 6, 4:30 pm
  Due: Tue May 7, 4:30 pm the end of scheduled exam time
  HW solutions will be posted in time
- Please fill out ICES survey! Time is running out!

Last time: interstellar dust
Q: what's the evidence?
Q: dust effects on radiation? why?
Q: what is the dust physically?

interstellar space filled with medium
that *absorbs* and *reddens* light
$\Rightarrow$ **interstellar dust**

quantify absorption via **extinction** A_λ

$$\frac{F_\lambda}{F_\lambda^0} = 10^{-(2/5)A_\lambda} \tag{1}$$

extinction measures optical depth

$$A_\lambda = \frac{5}{2} \log_{10} e^{\tau_\lambda} = 2.5 \ \log_{10}(e) \ \tau_\lambda = 1.086 \ \tau_\lambda \ \text{mag} \tag{2}$$

Reddening

observed reddening implies A_λ stronger for shorter λ
$\rightarrow$ increases with $1/\lambda$

for source of known F_λ^0, can measure this
`www: extinction curve as a function of wavelength`
observed trend: "*reddening law*"

- general rise in A_λ vs $1/\lambda$
- broad peak near $\lambda \sim 2200$ AA $= 0.2\mu$ m

Q: implications of peak? of reddening at very short λ?

in photometric bands, define *redding* or *selective extinction*:
for passbands B and V

$$E(B-V) \equiv A_B - A_V \tag{3}$$

Q: what is selective extinction for "grey" dust $\sigma_\lambda = const$?

interstellar dust: *microscopic irregular solid bodies*
effect on radiation:

- completely absorb wavelengths $\lambda \ll a_{\text{dust}}$ dust size
- scattering/absorption for $\lambda \sim a_{\text{dust}}$
- small effects for $\lambda \gg a_{\text{dust}}$

implications of extinction curve:

- peak wavelength $\rightarrow$ characteristic *dust size* $r_{\text{dust}} \sim 0.2\mu\text{m}$
- expect reddening at $\lambda \sim r_{\text{dust}}$
  but complete extinction for $\lambda \ll r_{\text{dust}}$
- reddening at small $\lambda \rightarrow$ some very small dust grains exist

note that extinction depends on sightline distance
but not *ratios* of extinction at different λ

$$R_V \equiv \frac{A_V}{A_B - A_V} = \frac{A_V}{E(B-V)} \approx \frac{\sigma_V}{\sigma_B - \sigma_V} \tag{4}$$

- Milky Way ISM typically has $R_V = 3.1$
- but within the MW, R_V varies across sightlines
  from $R_V \sim 2.1$ to ~ 5.7

A Clue: Interstellar Depletion

Experiment:

- measure local interstellar *atomic absorption lines* that appear in the spectra of nearby bright stars, e.g., ρOph
- infer *interstellar abundances*, and express as ratio: element/H
- compare with *solar system abundances* for element/H e.g., $(C/H)_{\rm ism,obs}$ vs $(C/H)_\odot$

Results:

- for some elements, abundances similar e.g., $(Ar/H)_{\rm ism,obs} \approx (Ar/H)_\odot$, and $(O/H)_{\rm ism,obs} \approx 0.5\ (O/H)_\odot$
- but other elements show strong **depletion** e.g., $(Fe/H)_{\rm ism,obs} \lesssim 10^{-2}\ (Fe/H)_\odot$, and $(Ca/H)_{\rm ism,obs} \approx 2 \times 10^{-4}\ (Ca/H)_\odot$

Q: why this difference?

Dust: Composition

interstellar *atomic absorption lines* trace
element in *atomic* form
$\rightarrow$ measure interstellar *gas-phase abundances* only!

but *dust* particles are in *solid phase*! “*grains*”
do not give atomic lines!

nearby ISM likely nearly has *nearly solar composition*
but some elements mostly in gas phase, others mostly in grains

Depletion pattern correlated with **condensation temperature**
i.e., temperature at which a dilute vapor $\rightarrow$ 50% solid

`www: observed depletion pattern`

- *low $T_{\rm cond}$ elements*: *volatile* (Kr, Ar, C, O, ...)
  small/no depletion
- *high $T_{\rm cond}$ elements*: *refractory* (Fe, Ni, Ti, Ca, ...)
  large depletion

Q: what is this trying to tell us?

depletion correlated with condensation temperature

suggests physical picture:

- dust formed out of high-temperature material
  e.g., ejecta from dying stars
  note: AGB stars have dusty shells
- as this vapor cools, refractory elements form dust first
- small depletion for $T_{\rm cond} \lesssim 700 - 800$ K
  either gas never gets this cool,
  or more likely, density becomes too low to form dust
  by collisional processes

Warning!

when using interstellar abundances, never forget that
these only include elements in the gas phase!

Dust Temperature

We have seen: interstellar dust absorbs starlight
but what happens next?

long story short:

- energy from photons is *thermalized* in dust grains
- which then *radiate* as black bodies
- dust temperature set by absorption/emission equilibrium at $T_{\text{dust}} \sim 10 - 100$ K, depending on environment
- observable in the *infrared*

`www: the sky in mid-far infrared`

Lesson: *dust reprocesses starlight into thermal IR!*

Implication:

starlight dominated by luminous massive stars

$\rightarrow$ dust IR emission traces extincted UV/optical from these stars

$\rightarrow$ probes star formation rate!

Gamma Rays

MeV Gamma Rays

consider photons with $E_\gamma \sim 0.5 - 10$ MeV
these have been observed astrophysically

Q: what physical processes can make MeV gammas?
hint: some we have discussed already, some we have not...

Q: what are possible astrophysical sites for these processes

MeV Gamma Rays: Emission Processes

MeV photons are high energy
can be made by nonthermal processes we have already seen

- nonthermal bremsstrahlung from cosmic-ray electrons
- inverse Compton of starlight by cosmic-ray electrons

But the MeV scale has other charms

- $m_e c^2 = 0.511$ MeV
  positron annihilation $e^{\pm} \to \gamma\gamma$
  emits back-to-back 511 keV photons (in rest frame)
- *atomic nuclei are quantum bound states*
  with energy level spacings ~ 1 MeV
  `www: nuclear energy level diagram`

Astrophysical sources?

- positrons $e^+ \to 511$ keV photons
- excited nuclei $\to$ MeV lines

The MeV Sky

The 511 keV Sky `www: sky map`
line emission seen!
concentrated in Galactic center, but not point source
this requires huge numbers of positrons!
an open question where they came from
decay of radioactive nucleosynthesis products? cosmic rays? dark matter?

The 1.8 keV Sky `www: sky map`

aluminum isotope ^{26}Al is unstable: $t_{1/2} = 1.5$ Myr

decays to excited state: $^{26}\text{Al} \rightarrow {}^{26}\text{Mg}^{*} \rightarrow {}^{26}\text{Mg}^{\text{g.s.}} + \gamma$

each decay produces 1.8 MeV line

emission seen across Galactic plane

$\rightarrow$ requires "fresh" ^{26}Al

$\rightarrow$ nucleosynthesis is ongoing in the Galaxy

$\rightarrow$ line intensity measures Milky Way star formation rate

GeV and TeV Gamma Rays

consider photons with $E_\gamma \sim 1$ GeV to 10 TeV $= 10^{12}$ eV
these have been observed astrophysically

Q: what physical processes can make GeV/TeV gammas?
hint: some we have discussed already, some we have not...

Q: what are possible astrophysical sites for these processes

GeV/TeV Gamma Rays: Emission Processes

GeV/TeV photons have gi-normous energies
difficult to make even with cosmic-ray electrons
inverse Compton can work, but requires electrons with $E_e \gg E_\gamma$
these lose energy fast: $(dE_e/dt)_{\rm IC} = 4/3\ \sigma_{\rm T} u_{\rm bg} \gamma^2$

But the GeV/TeV scale has other charms
- *cosmic-ray protons* interact with interstellar proton (hydrogen)

$$p_{\rm cr} + p_{\rm ism} \rightarrow pp\pi^0 \qquad (5)$$

makes *neutral pi-meson* ("pion") π^0
rapidly decays: $\pi^0 \rightarrow \gamma\gamma$, with $E_\gamma = m_\pi c^2/2 = 67$ MeV
but decay is *in flight*: on γ boosted to high energy
- *dark matter* is expected to be an elementary particle
  an in many models can annihilate with itself
  annihilation products are known (Standard Model) particles
  which can make gamma rays

The GeV and TeV Sky

The GeV Sky `www: Fermi sky map`
diffuse emission predominanty in *Galactic plane*

makes sense! $p_{\rm cr} + p_{\rm ism} \to \pi^0 \to \gamma\gamma$ requires both
- cosmic ray proton *projectiles*, but also
- interstellar hydrogen *targets*

and the Galactic gas lives in the disk plane

Implications:
Galactic γ-ray intensity $I_\gamma \propto N(\mathrm{H_{tot}})$: total hydrogen column
tests other measures of neutral, molecular, and ionized H

GeV Point Sources

- in Galactic plane: pulsars
- out of plane: AGN, star-forming galaxies

The TeV Sky `www: H.E.S.S. Galactic plane map`

- Galactic plane: supernova remnants (resolved!)
- extragalactic: blazars
- Galactic center: TeV signal seen!
  why? open question
  large cosmic ray flux? Sgr A*? dark matter?

Finale

The Multiwavelength Sky Revisited

continuum emission at the lowest and highest energies
radio continuum, GeV and TeV
emission is *nonthermal*, due to cosmic rays

line emission important at low and high energies

- atoms: 21 cm
- molecules: CO
- nuclei: ^{26}Al
- annihilation: e^+e^-

continuum emission intermediate energies: *thermal*

- starlight
- dust emission = reprocessed starlight

Flexing Your Radiative Muscles

We have come a long way!

You now know – at least in outline –

- how to *predict* the way things *should look*
- how to *understand* the way things *do look*

We only had time to scratch the surface
but you have the tools now to learn more
...and to teach us all more!

Go forth and radiate!

Thank You!