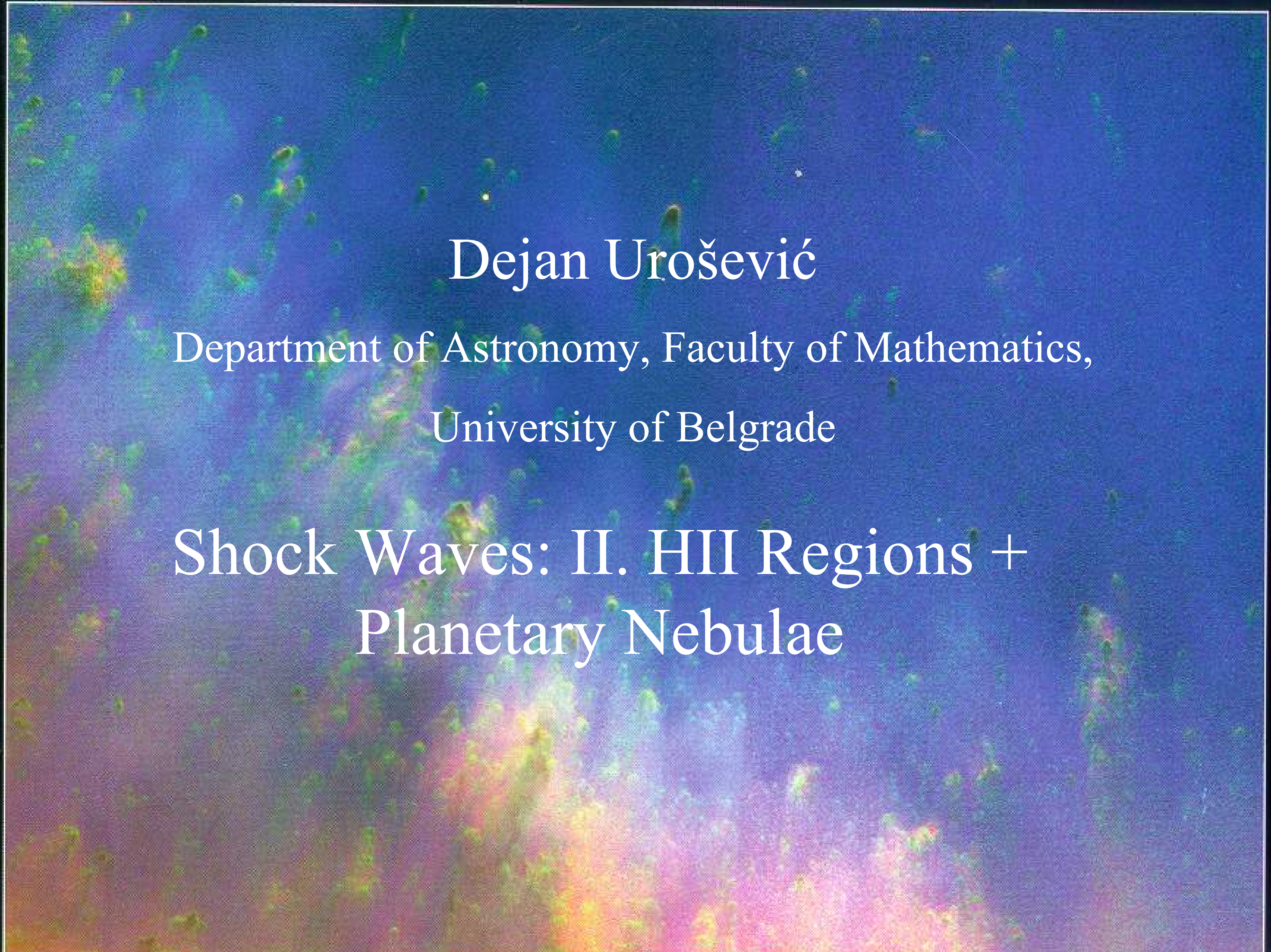

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Shock Waves: II. HII Regions + Planetary Nebulae

Ionization Fronts and Shocks in HII Regions

- two stages of evolution of the HII regions:

  - first stage: formation of "initial Stromgren sphere" by an ionization front

  - second stage: expansion of a shock wave followed by an ionization front

Ionization Fronts and Shocks in HII Regions

- first stage
  - duration: few thousand years
  - fast propagation of a wave of ionization
  - up to an equilibrium radius R_{init} (initial Stromgren sphere)

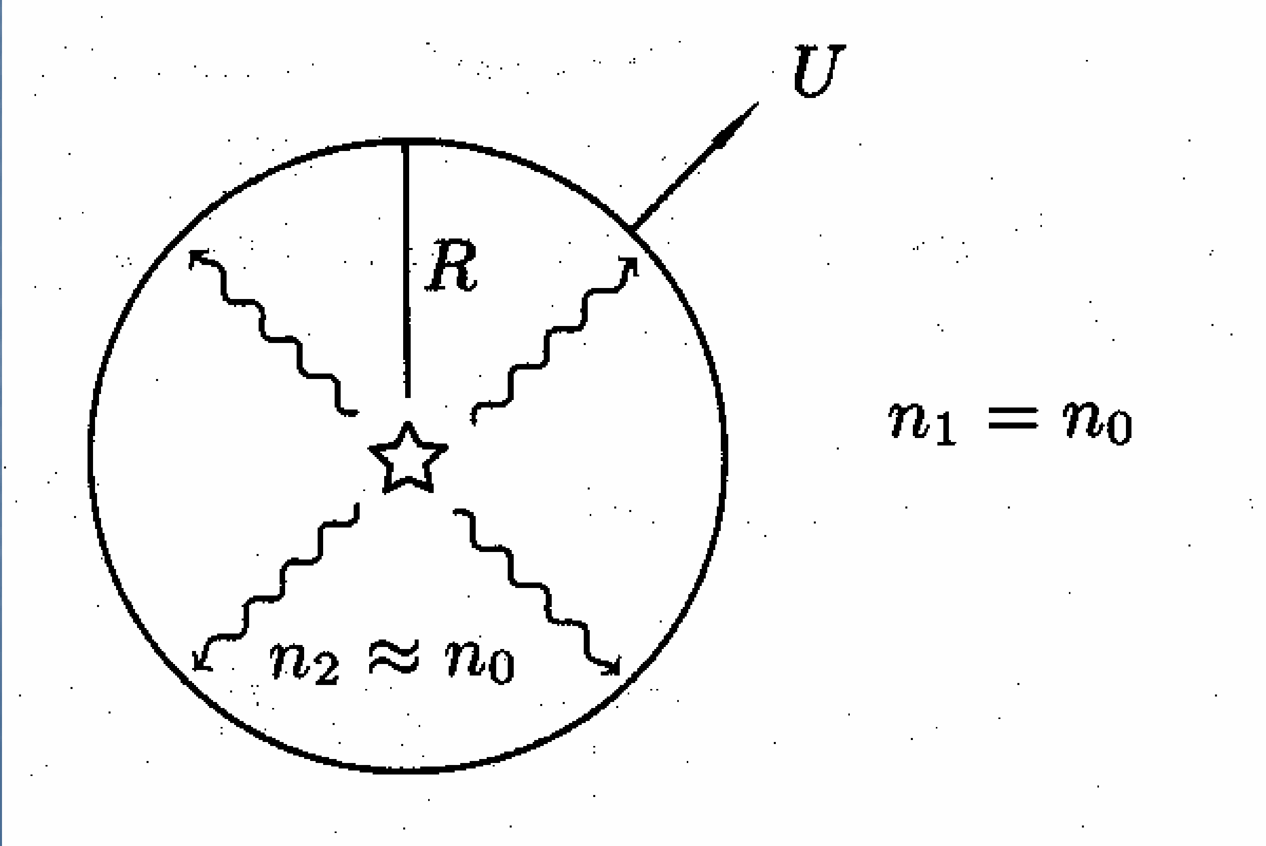
ionization = recombination

$$R_{init} \sim 5.6 \text{ pc}$$

(O5 star born into a region of density 100 cm^{-3})

Ionization Fronts and Shocks in HII Regions

- idealized first stage:



Ionization Fronts and Shocks in HII Regions

- second stage

  - pressure of HII region > pressure of HI region

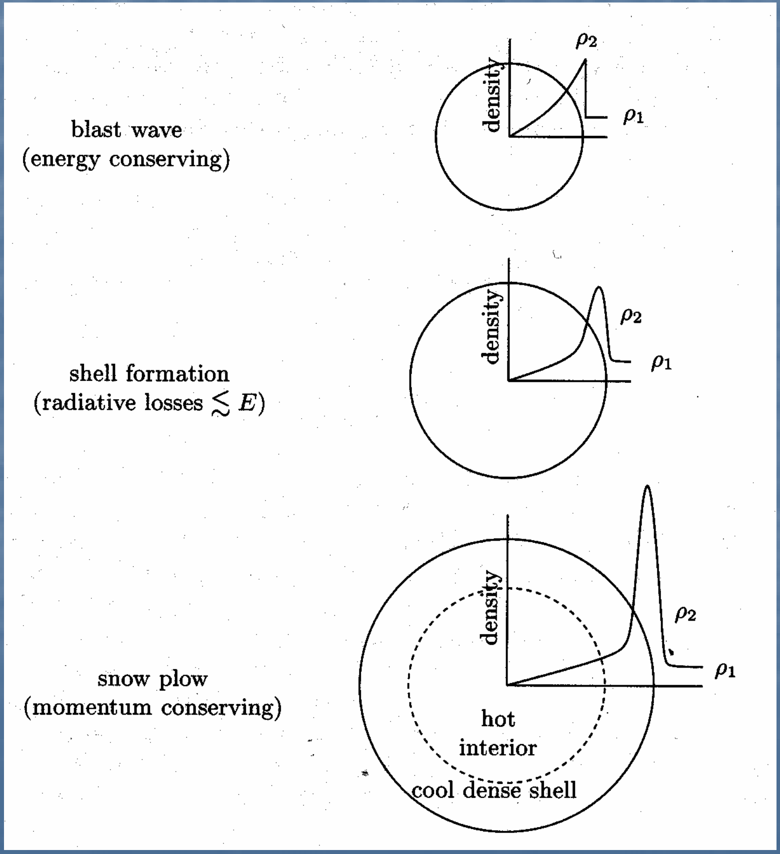
  - the isothermal shock wave is formed

  - volume of the HII region increases => its density decreases => recombination rate decreases =>

  - the ionization front is formed again and follows the shock wave

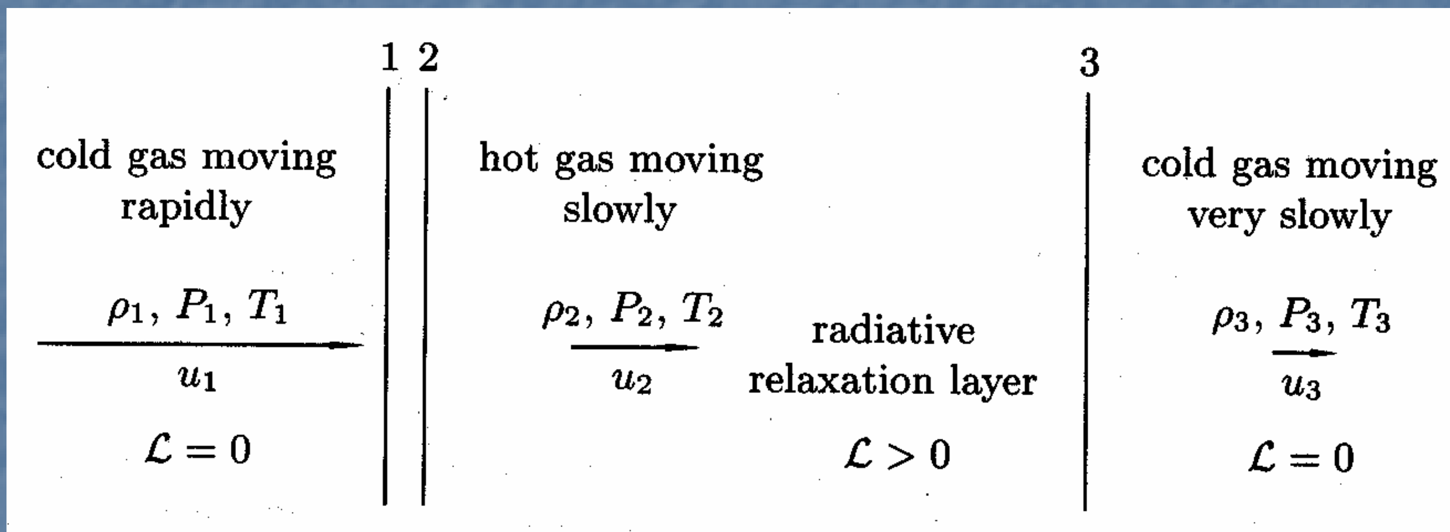
Ionization Fronts and Shocks in HII Regions

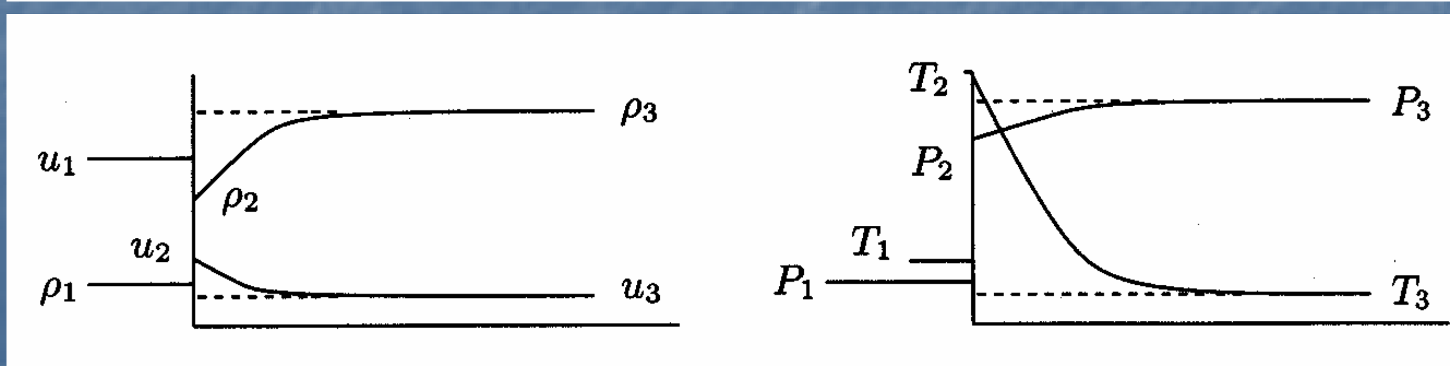
- isothermal shock wave



Ionization Fronts and Shocks in HII Regions

- radiative shocks





Ionization Fronts and Shocks in HII Regions

- isothermal shock

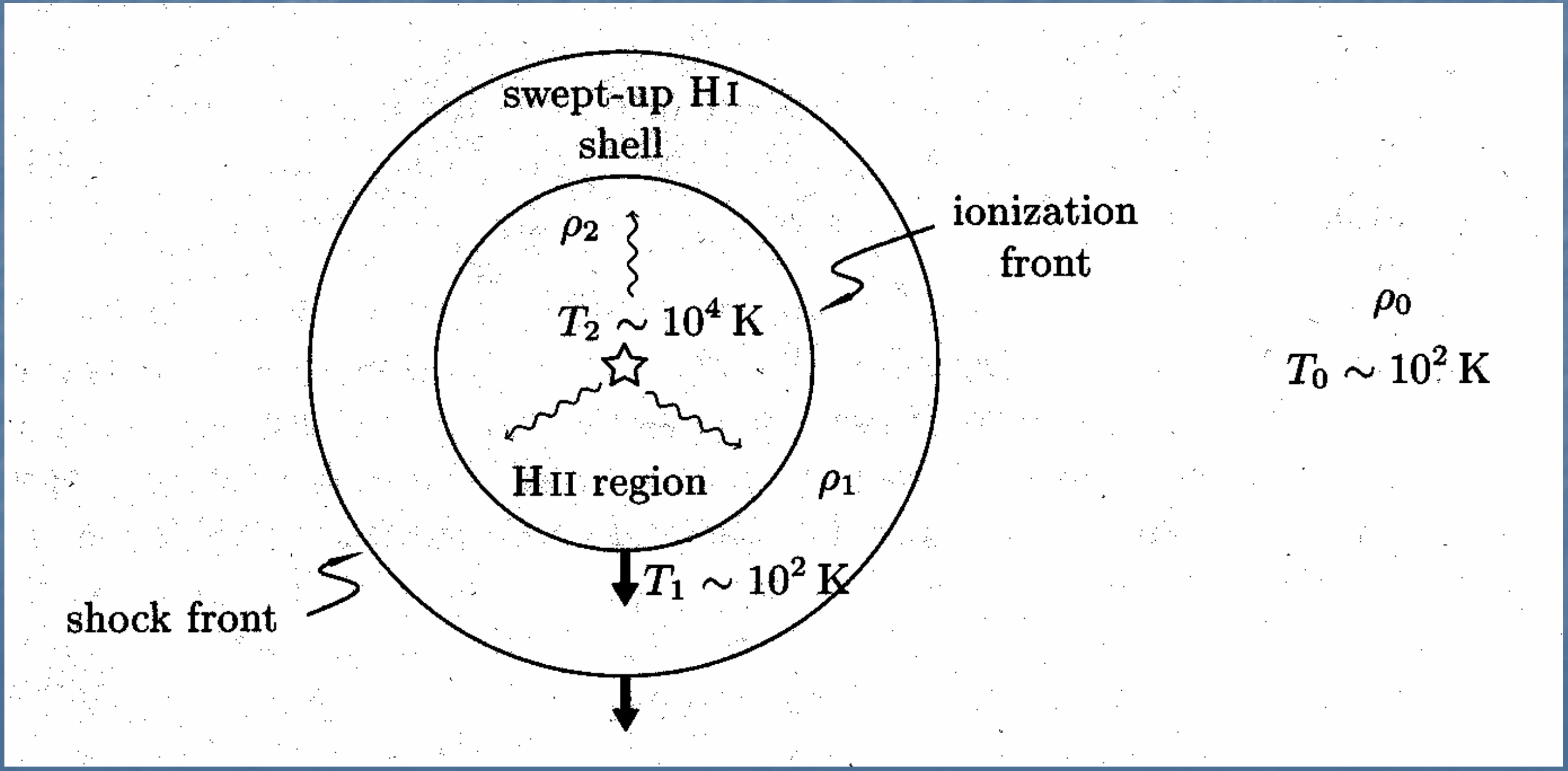
  compression:

$$\rho_2/\rho_1 \sim (\text{Mach number})^2$$

$$\text{Mach number} = u_1/v_{s,T}$$

Ionization Fronts and Shocks in HII Regions

- idealized second stage:



Ionization Fronts and Shocks in HII Regions

- second stage
  - duration: few tens million years
  - up to an final equilibrium radius R_{final} (final Stromgren sphere)

ionization = recombination

+

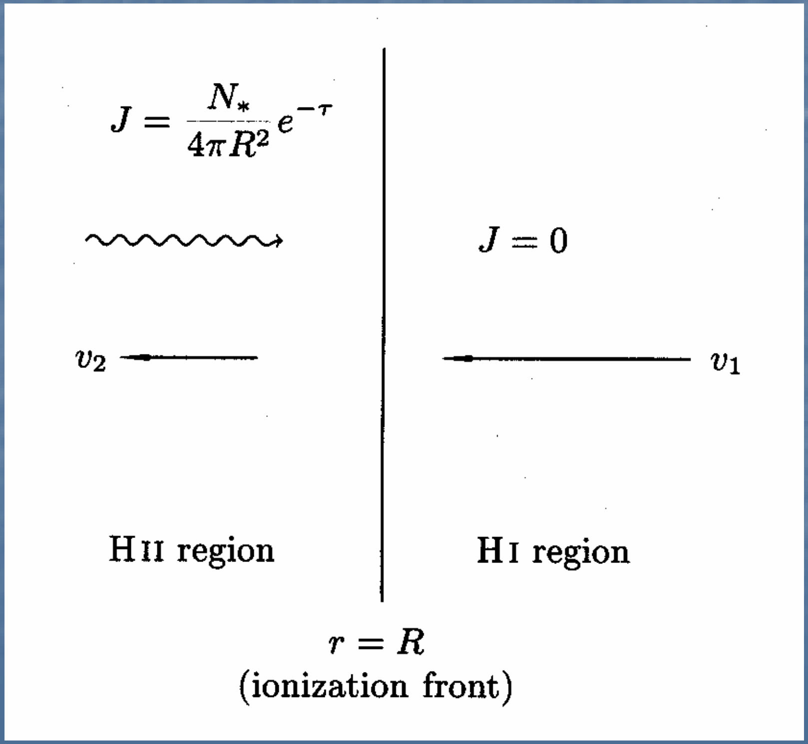
$V_{shock\ wave} \sim 10$ km/s

$R_{final} \sim 200$ pc

(if central star does not finish its life as SN earlier!)

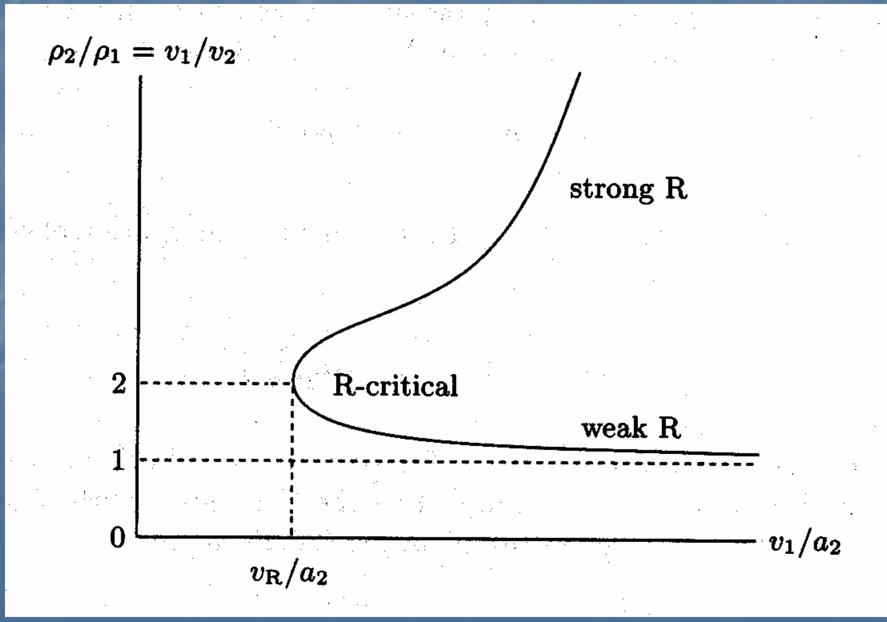
Ionization Fronts and Shocks in HII Regions

- Ionization fronts



Ionization Fronts and Shocks in HII Regions

- first expansion phase – R-type ionization fronts
  - R (rarefied gas in upstream region)
  - R-fronts – supersonic
    v_1 ~ 1300 km/s, for strong R-fronts
    (5.6 pc, 5000 years)
  - R-compression ~ 8/3



Ionization Fronts and Shocks in HII Regions

- transition to D-type ionization fronts

an R-critical ionization front

||

an isothermal shock + a D-type critical front

Ionization Fronts and Shocks in HII Regions

- second expansion phase – D-type ionization fronts + isothermal shock

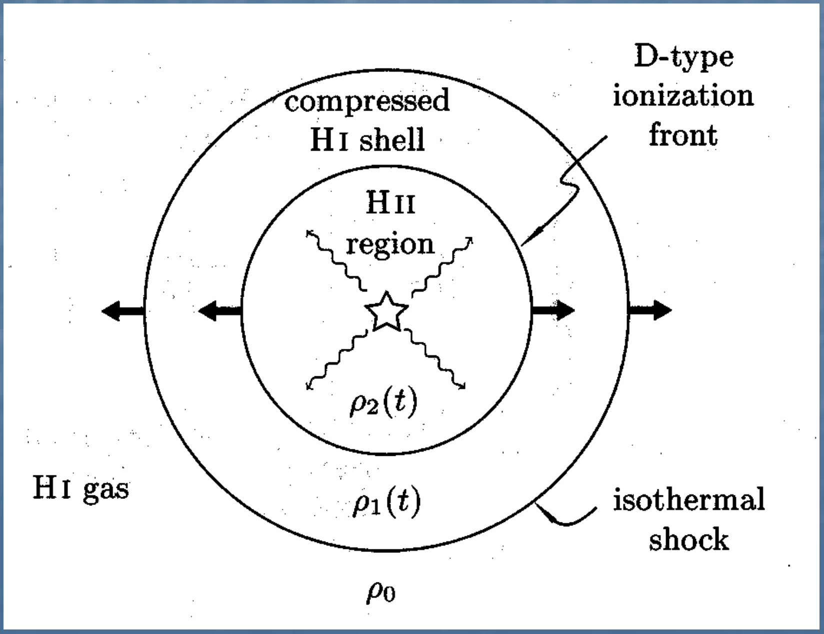
  - D (dense gas in upstream region)

  - D-fronts - subsonic

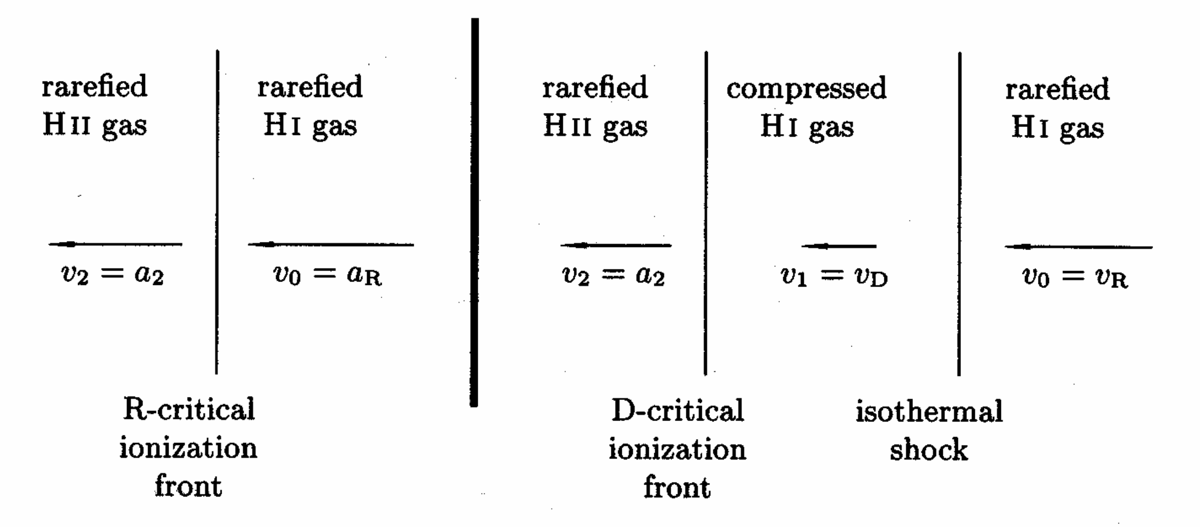
    ~0.2 km/s

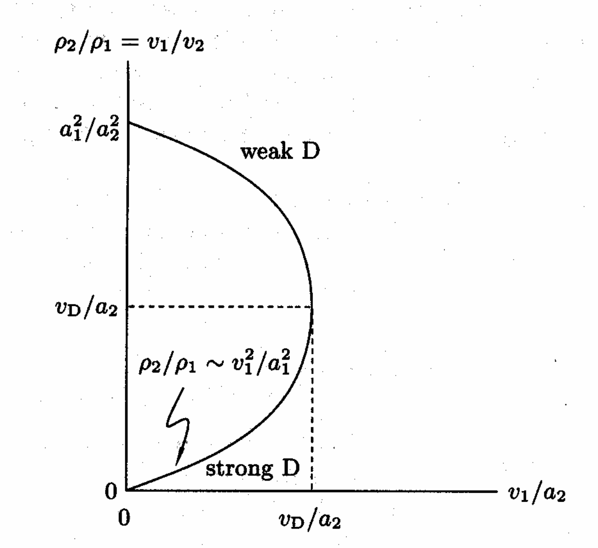
  - D-compression

    ~1/60



Ionization Fronts and Shocks in HII Regions





Ionization Fronts and Shocks in HII Regions

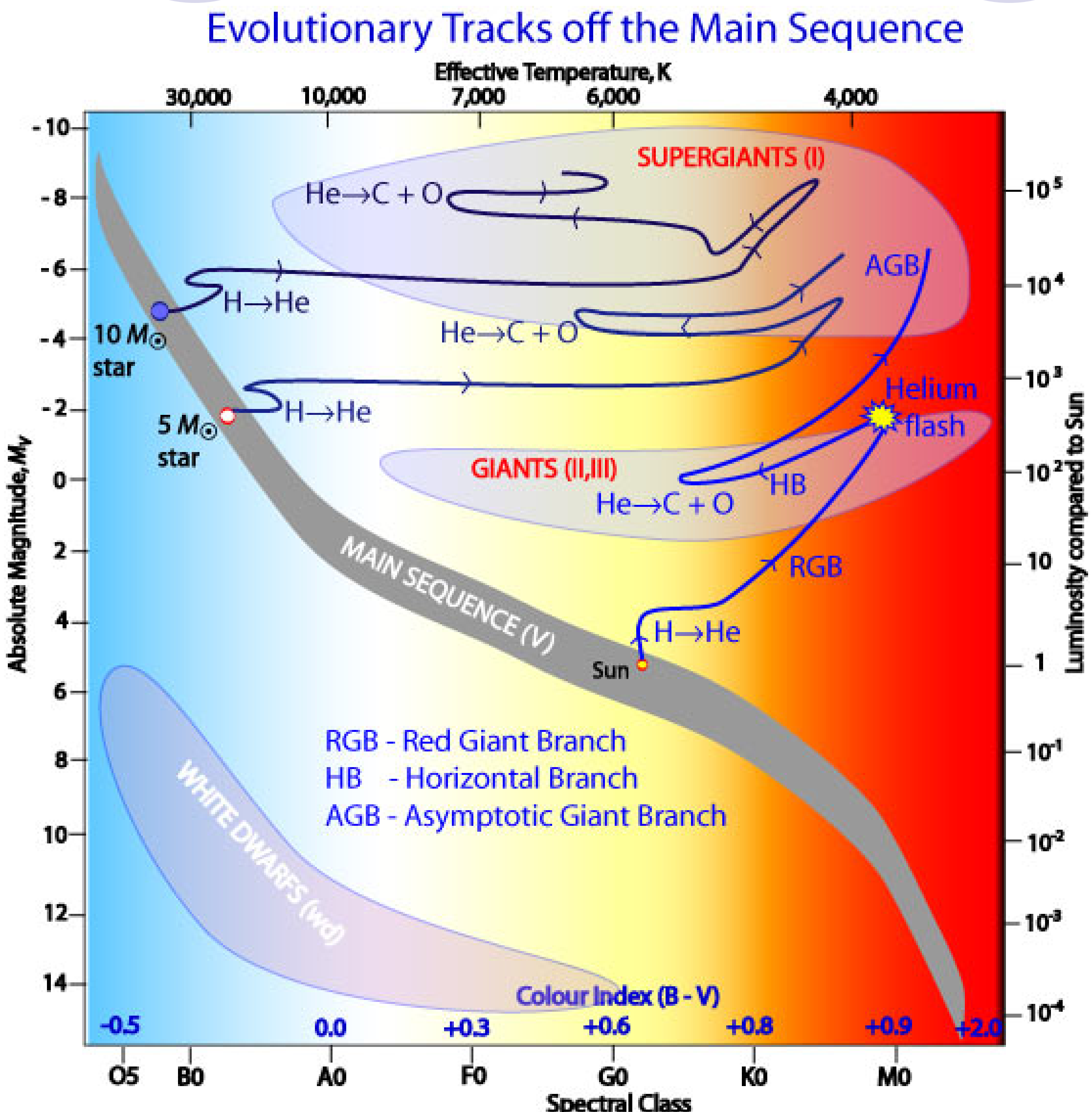
- real duration of evolution of an HII region is defined by lifetime of O5 star!

  -it is approx. 30 times less than lifetime of second expansion phase

$$R_{\text{final}} \sim 20 \text{ pc}$$

F. Shu: "A typical HII region spends most of its life in a fully dynamic state of expansion and ends its existence as part of the debris of a supernova remnants."

Planetary Nebulae and Associated Shocks



Planetary Nebulae and Associated Shocks

- asymptotic giant branch stars (AGB) – progenitors of planetary nebulae (PNe)
- AGB stars: C-N-O degenerate core + mostly H (or He) reactions in a thin envelope
- AGB mass loss 10^{-5} M_{Sun}/yr, V_{wind} ~ 10 km/s,
- duration of the AGB phase ~ million years
- when H envelope is completely removed, AGB phase is finished
- temperature of an exposed core increases – central star of PN

Planetary Nebulae and Associated Shocks

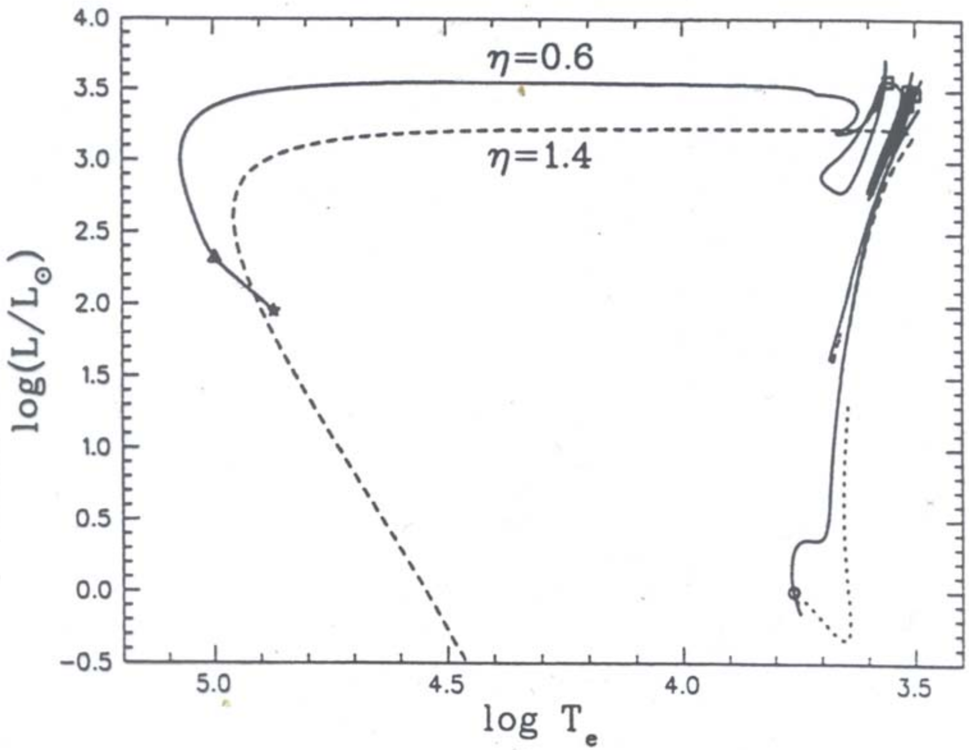


FIG. 5.—The Sun's evolution in the HR diagram, from the pre–main-sequence state to the pre–white dwarf stage. For our preferred mass-loss case (*solid curve*: $\eta = 0.6$), the triangle indicates the beginning of the final helium shell flash, and the star its peak, where computations were terminated. The dashed curve shows our extreme mass-loss case ($\eta = 1.4$), which leaves the RGB to become a helium white dwarf.

Planetary Nebulae and Associated Shocks

- PN = central star + ejected AGB material
- central stars (CS) – the hottest stars in Galaxy, up to 100 000 K
- CS mass loss 10^{-8} M_{Sun}/yr, V_{wind} ~ 2000 km/s
- when H is exhausted, CS enters in cooling track toward WD
- the PN evolution is finished after 10 000 yr

Planetary Nebulae and Associated Shocks

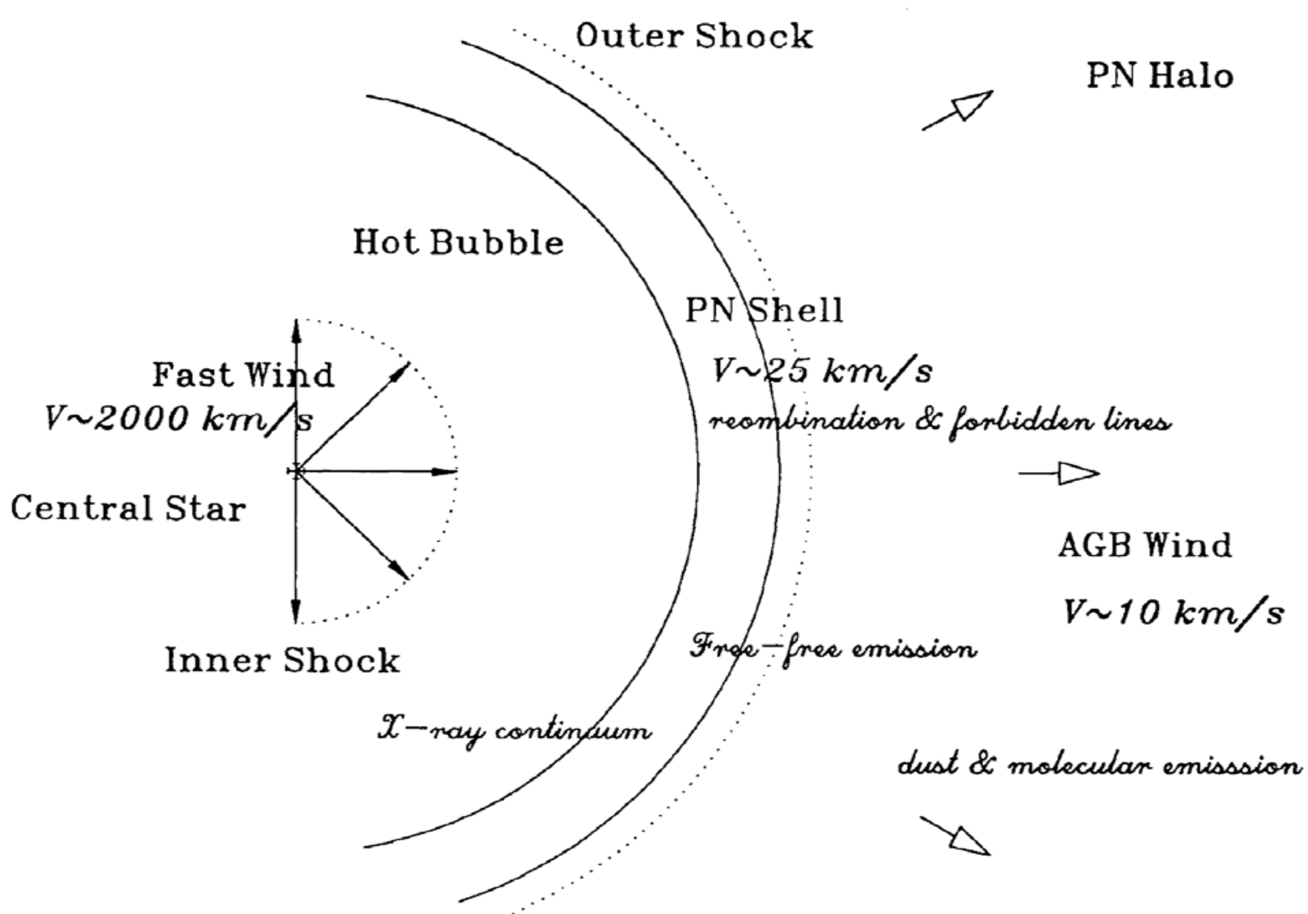
- the interacting stellar winds model

  - two shocks:

    inner (energy conserving)

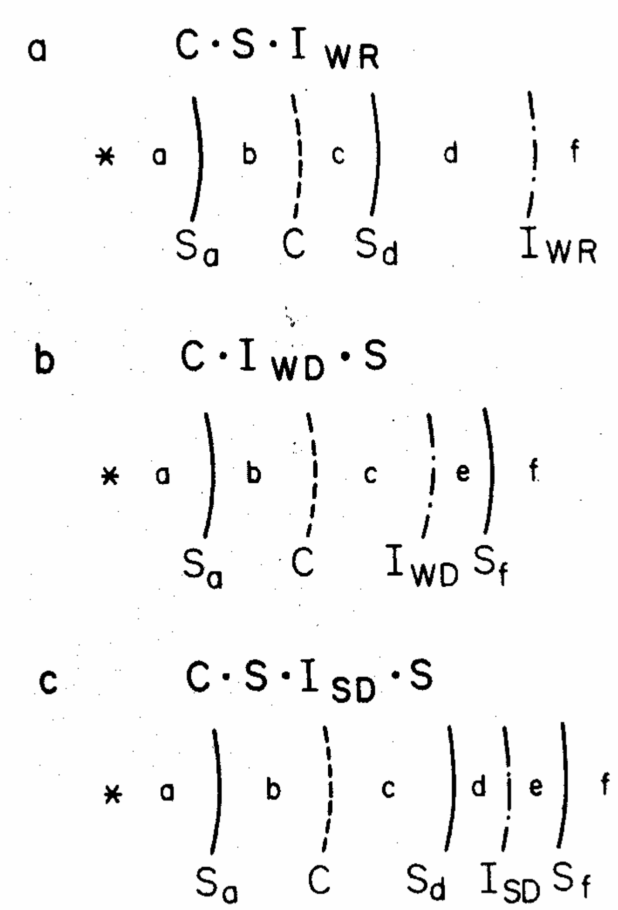
    outer (momentum conserving – isothermal)

Planetary Nebulae and Associated Shocks



Planetary Nebulae and Associated Shocks

- PN is HII region – we expect Ionization fronts



Planetary Nebulae in Radio

- HII regions – thermal bremsstrahlung emission from medium perturbed by isothermal shock
- we derived the theoretical *Σ-D* relation for planetary nebulae

$$\Sigma \sim D^{-3}$$

(density $n \sim D^{-2}$, T = const. ~ 10 000 K)

Urošević, Vukotić, Arbutina, Ilić (2007)

Planetary Nebulae in Radio

- empirical Σ-D relation for PNe
- our results show that no valid empirical correlation between the radio surface brightness and diameters of PNe
- reasons: peculiar physics and selection effects

Planetary Nebulae in Radio

- samples

No.	Sample[a]	$\beta_{\Sigma-D}$	$r_{\Sigma-D}$	α_{L-D}	r_{L-D}	N
01	Phillips 2002 T1,T2	-2.39± 0.16	0.86	-0.39 ±0.16	0.26	78
02	Phillips 2002 T1	-2.22± 0.15	0.89	-0.22 ±0.15	0.19	56
03	Phillips 2002 T2	-3.29± 0.33	0.91	-1.29 ±0.33	0.66	22
04	Phillips 2002 T1 <0.3	-1.44± 0.39	0.83	0.56 ±0.39	0.50	8
05	Phillips 2002 T1 <0.5	-1.81± 0.30	0.81	0.19 ±0.30	0.14	22
06	Phillips 2002 T1 <0.7	-2.07± 0.19	0.86	-0.07 ±0.19	0.056	44
07	Phillips 2002 T1,T2 †	-2.56± 0.13	0.91	-0.56 ±0.13	0.44	75
08	Phillips 2002 T1 †	-2.40± 0.11	0.95	-0.40 ±0.11	0.44	53
09	Phillips 2002 T1 <0.3 †	-2.13± 0.43	0.91	-0.13 ±0.43	0.14	7
10	Phillips 2002 T1 <0.5 †	-2.30± 0.21	0.93	-0.30 ±0.21	0.32	19
11	Phillips 2002 T1 <0.7 †	-2.36± 0.13	0.94	-0.36 ±0.13	0.40	41
12	Van de Steene & Zijlstra 1995	-2.41± 0.34	0.84	-0.41 ±0.34	0.26	23
13	Zhang 1995	-2.17± 0.14	0.80	-0.17 ±0.14	0.10	132
14	USNO-PN	-2.38± 0.56	0.90	0.38 ±0.56	0.32	6

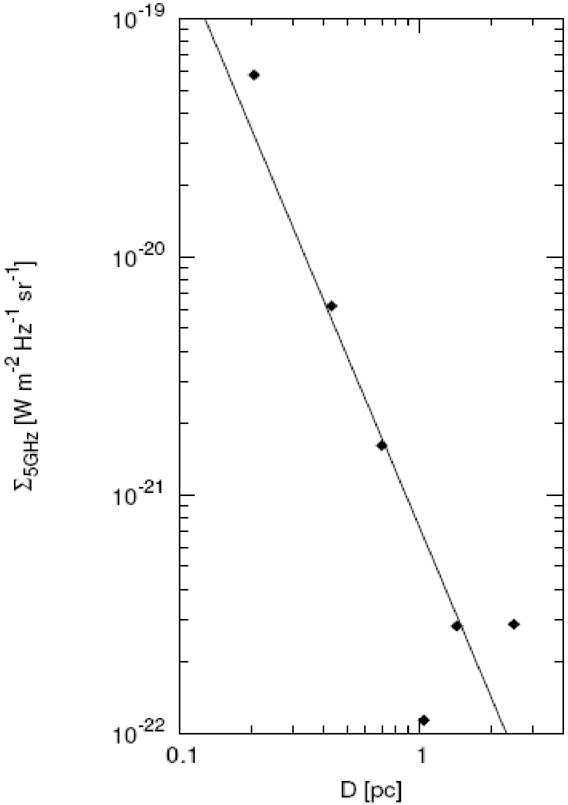
Planetary Nebulae in Radio

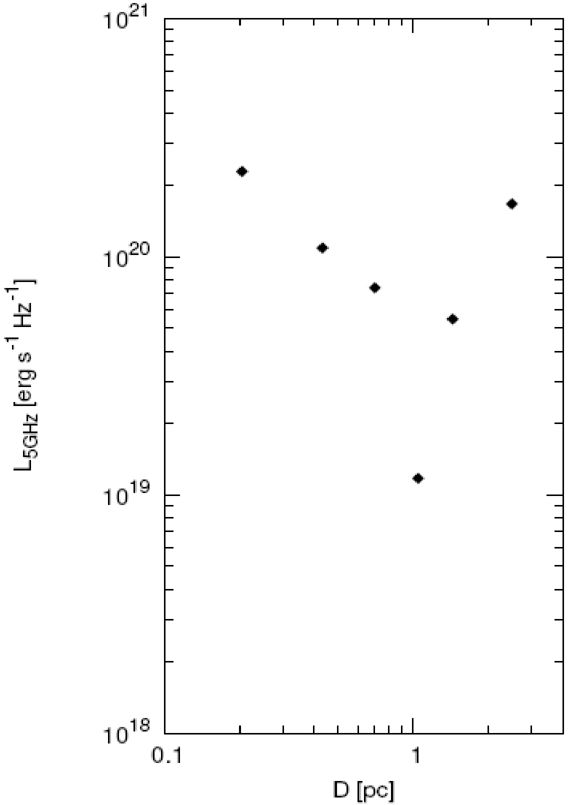
- USNO sample

Name	trigonometric parallax [mas]	S_{5GHz} [mJy]	diameter [″]
NGC 7293 (036.1-57.1)	4.56 ± 0.49	1292[a]	660[b]
NGC 6853 (060.8-03.6)	3.81 ± 0.47	1325[a]	340[a]
NGC 6720 (063.1+13.9)	1.42 ± 0.55	384[a]	60[c]
A 21 (205.1+14.2)	1.85 ± 0.51	157[d]	550[e]
A 7 (215.5-30.8)	1.48 ± 0.42	305[a]	760[a]
A 24 (217.1+14.7)	1.92 ± 0.34	36[a]	415[d]

Planetary Nebulae in Radio

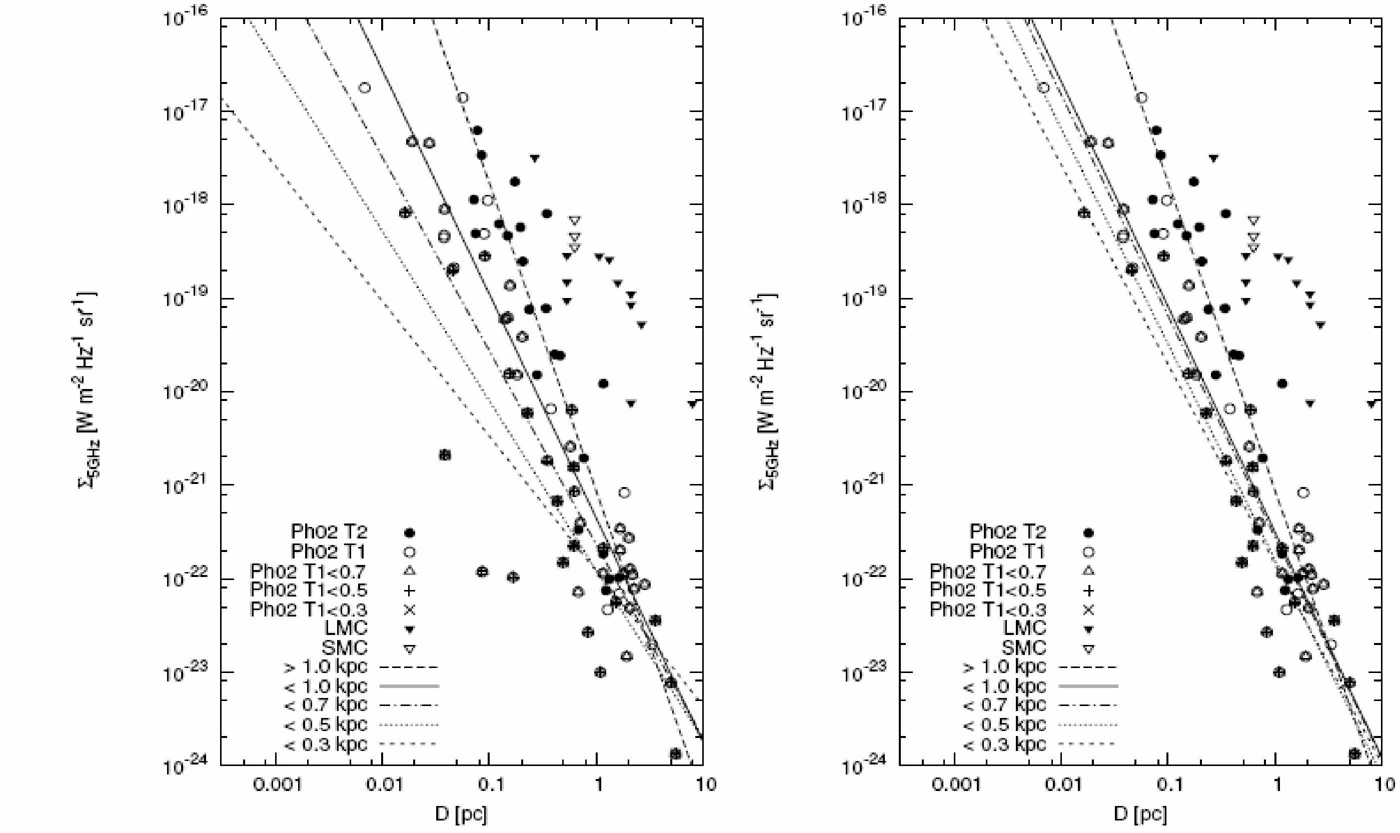
- USNO *Σ-D* and *L-D* diagrams





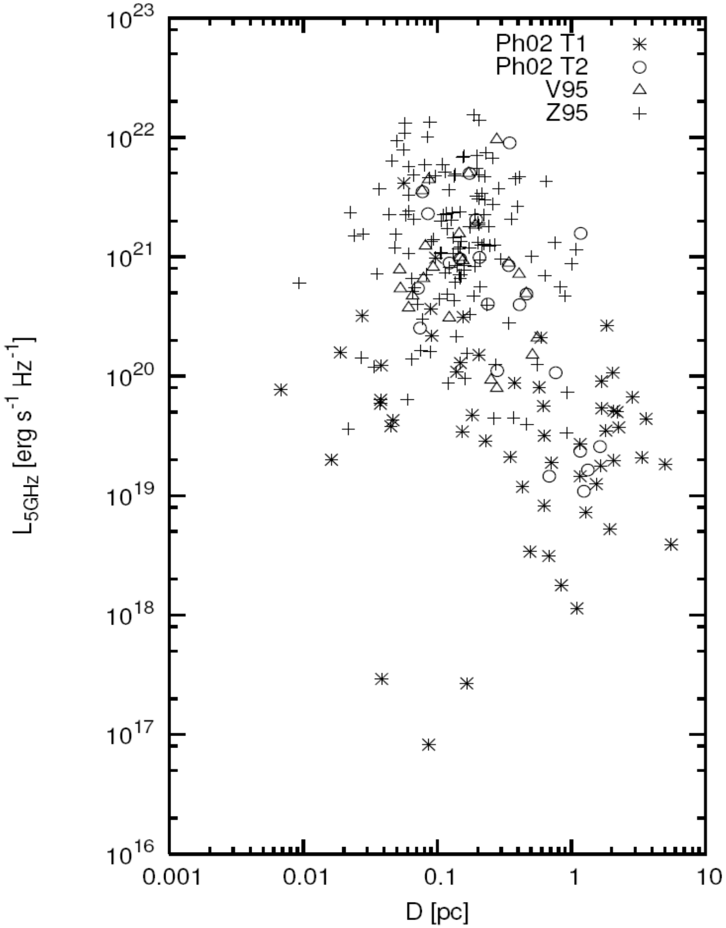
Planetary Nebulae in Radio

- the *Σ-D* fits for 5 selected samples of PNe



Planetary Nebulae in Radio

- the *L-D* diagram of PNe



Planetary Nebulae in Radio

These are results of collaboration by many of "us" here:

Vukotić, Arbutina, Ilić,Filipović,Bojičić, Šegan and Urošević

submitted to A&A

Plans for future

- plans for tomorrow

  - the *Σ-D* relation for “ordinary” HII regions

- plans for day after tomorrow

  - development of HD and MHD codes for the evolution of SNR and PN (HII) shock waves (and fronts)

THANKS AGAIN!!!