THERMONUCLEAR REACTION RATES FOR ASTROPHYSICAL APPLICATIONS

WORKSHOP CONCLUSIONS

TEN COMMANDMENTS



THE TEN COMMANDMENTS OF NUCLEAR ASTROPHYSICS

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TEN RECOMMANDATIONS/SUGGESTIONS IN NUCLEAR ASTROPHYSICS/ ASTRONUCLEAR PHYSICS



TRY HARD TO DEVELOP AT LAST A TRUE NUCLEAR ASTROPHYSICS/ ASTRONUCLEAR PHYSICS UNIFIED COMMUNITY

THE ASTRONOMERS-ASTROPHYSICISTS



THE TRIBE OF THE THEORETICIANS (TRIBE TA)



THE TRIBE OF THE OBSERVERS (TRIBE OA)

THE NUCLEAR PHYSICISTS OF THE EXTREMELY LOW ENERGIES



THE TRIBE OF THE EXPERIMENTALISTS (TRIBE EN)

THE TRIBE OF THE THEORETICIANS (TRIBE TN)



THE IDEAL NUCLEAR ASTROPHYSICIST

• PERFECT GENETIC FORMULA :

OA + TA + EN + TN



AN EXAMPLE OF A STILL ACCEPTABLE GENETIC FORMULA : TA + TN

A SECOND-CLASS HYBRIDS: STILL VERY RARE CREATURES

PUT EFFORT IN THE IDENTIFICATION OF THE MATHEMATICAL PROPERTIES OF THE SIMPLEST SYSTEM OF BASIC EQUATIONS OF STELLAR STRUCTURE, EVOLUTION

UNICITY OF THE SOLUTION FOR SPHERICALLY SYMMETRIC QUASI-STATIC MODEL STAR?

GO BEYOND - VOGT-RUSSELL « THEOREM »

- X-Y-Z COMPOSITION BLEND

- BIFURCATIONS (e.g. Kaehler, 1977)

- CHAOS

« chaos is likely to be an ingredient of the evolution process in stars » (Perdang, 1995)

GO BEYOND ONE-DIMENSIONAL MODELS FOR NON-EXPLODING STARS

NOTE 1: $1D \rightarrow 2D \rightarrow 3D$ NOT JUST

NOT JUST A PROGRESSION DUE TO COMPUTATIONAL RESOURCES...

... BUT ALSO A PROGRESSION IN THE UNDERSTANDING OF COMPLEX PHYSICAL PHENOMENA!

- DEFINITION OF CONVECTIVE ZONE BOUNDARIES NEEDS MORE COMPLETE PHYSICS
- STABILITY OF BURNING IN A CONVECTIVE REGION ?
- CORRECT TREATMENT OF ROTATION, MAGNETIC FIELDS Esp. : consistent treatment of shear flows from differential rotation and from convection

NOTE 2: INTERESTING TO LEARN FROM EXPERIMENTS CONDUCTED IN THE LABORATORY!

A 2D AND 3D SIMULATION OF THE INTERFACE BETWEEN CONVECTIVE H- AND He-BURNING SHELLS IN A LOW-MASS STAR



Fig. 6. (a) Temporal evolution of the angle-averaged radial distribution of (the logarithm of) the hydrogen mass fraction for the 3D model hifexp.3d.f, and (b) for the 2D model hifexp.2d.f, respectively. The dashed lines delineate the boundaries of the newly forming hydrogen-burning convection shell, and the dotted line marks the bottom of the helium-burning convection zone.

A 2D SIMULATION OF THE C, Ne, O AND Si SHELL BURNINGS AROUND THE Fe CORE ABOUT 1 HOUR BEFORE COLLAPSE OF A NON-ROTATING NON-MAGNETIZED $Z_{\odot}\,23~M_{\odot}\,$ STAR





NON-SPHERICAL, HIGHLY DYNAMICAL INTER-SHELL MIXING IN SN PROGENITOR!

SOME SHORTCOMINGS

- INITIAL 1D MODEL
- MASS, DYNAMICS OF THE Fe CORE NOT PROPERLY FOLLOWED
- ROTATION, MAGNETIC FIELD TO BE INCLUDED
- 3D SIMULATIONS NEEDED!

ASK YOUR COMPUTER TO PRODUCE A 3D SUPERNOVA EXPLOSION OF MASSIVE ($M \ge 10 M_{\odot}$) STARS (NATURE DOES IT!)

- 1) EVEN WITH THE HELP OF A NEUTRINO WIND, 1D MODEL STARS DO NOT EXPLODE WITHOUT SOME ARTIFICIAL INPUT (SOME SPECIAL EXCEPTIONS)
- 2) IN ADDITION TO THE NEUTRINO WIND, 3D MODEL STARS MAY GET SOME BOOST FROM
 - MAGNETIC FIELDS
 - PROGENITOR ROTATION
 - FLUID INSTABILITIES
 - STRONG SOUND WAVES...

... BUT A COMPUTER-GENERATED EXPLOSION WITH AN ADEQUATE ENERGY REMAINS A NIGHTMARE

!!!!AND REMEMBER: ALL PRE-SN MODELS ARE WRONG!!!!

CLASSICAL RECIPE TO START MULTI-D SN SIMULATIONS: PERTURB 1D PRE-SN MODEL





350 s AFTER CORE BOUNCE 15.5 M⊙

900 s AFTER BOUNCE (SHOCK WAVE EMERGES AT STELLAR SURFACE)

Figure 2. Surfaces of the radially outermost locations with constant mass fractions of $\sim 3\%$ for carbon (green), and oxygen (red), and of $\sim 7\%$ for nickel (blue). The upper two panels show the directional asymmetries from two different viewing directions at 350 s after core bounce when the metal clumps begin to enter the helium layer of the star. The lower two panels display the hydrodynamic instabilities at about 9000 s shortly after the SN shock has broken out of the stellar surface. The side length of the upper panels is about 5×10^{11} cm, of the lower panels 7.5×10^{12} cm.

ALWAYS KEEP IN MIND THAT HYDRODYNAMIC NUCLEAR EXPLOSIONS ARE HIGHLY COMPLEX PROCESSES

> EXPLOSION SURFACE WHITE DWARFS (NOVAE)

EXPLOSION SURFACE NEUTRON STARS (X-RAY BURSTS)

BULK EXPLOSION WHITE DWARFS (TYPE Ia SNe)

TWO BROAD TYPES OF HYDRODYNAMIC BURNINGS

- DETONATION (SUPERSONIC SHOCK FRONT)
- DEFLAGRATION (SUBSONIC BURNING FRONT: « FLAME »)

BETTER GET THE HELP OF PROFESSIONAL HYDRODYNAMICISTS
NEVER USE HYDRO CODES AS BLACK BOXES!

MULTI-D SIMULATIONS OF FLAMES



Fig. 6.— Two-dimensional slices through a three-dimensional simulation of a compound carbon-oxygen flame. The panels are carbon mass fraction, oxygen mass fraction, oxygen burning rate and temperature, respectively.

GENERAL 3D STRUCTURE OF A FLAME 1.8 S AFTER IGNITION



GET RELIABLE EXPERIMENTAL DATA AND IMPROVE NUCLEAR MODEL PREDICTIONS FOR

> STATIC PROPERTIES

- BETA-DECAY PROPERTIES (+ v-NUCLEUS INTERACTIONS)
- FISSION PROPERTIES OF LARGE VARIETY OF (HIGHLY) EXOTIC NUCLEI (COLD + HOT !)
- ➢ EQUATION OF STATE
 - HOT SUPERNOVA CORES
 - COLD NEUTRON STARS

ALWAYS AIM FOR MICROSCOPISM

GET RELIABLE EXPERIMENTAL DATA AND IMPROVE MODEL PREDICTIONS FOR NUCLEAR REACTION CROSS SECTIONS AT ENERGIES OF ASTROPHYSICAL INTEREST

PUSH LABORATORY EFFORTS TO THEIR LIMITS

AIM FOR MICROSCOPISM

- EVALUATE REASONABLE IMPACT OF ESTIMATED UNCERTAINTIES IN RATES OR OTHER NUCLEAR DATA ON MEANINGFUL ASTROPHYSICS OBSERVABLES (RANDOM CHOICE OF UNCERTAINTIES!!)
- BEWARE HASTY CONCLUSIONS ABOUT NEED TO CONDUCT VERY DIFFICULT MEASUREMENTS IN ORDER TO BETTER UNDERSTAND THE COSMOS
 - NAIVETY HAS TO BE AVOIDED!
 - ALWAYS REMEMBER THAT EXTREMELY GOOD EXTREMELY LOW ENERGY NUCLEAR PHYSICS IS NECESSARY, BUT NOT SUFFICIENT TO DO GOOD ASTROPHYSICS!

AVOID TRYING TO INFER NUCLEAR PROPERTIES FROM THE MACROCOSM OF ASTROPHYSICS

FRED HOYLE DID IT: THE « HOYLE » STATE IN ¹²C (E*= 7.654 MeV)

TI IS VERY DANGEROUS TO TRY TO IMITATE HIM!

TWO EXAMPLES:

THE 3 α OR THE 12 C ($\alpha,\gamma)^{16}$ O REACTION RATES CONSTRAINED BY STELLAR MODEL CONSIDERATIONS

ALSO AVOID TRYING TO INFER THE VIRTUES OF A NUCLEAR MODEL FROM THE MACROCOSM OF ASTROPHYSICS

AVOID PLAYING SISYPHUS



SISYPHUS WAS A KING PUNISHED BY BEING COMPELLED TO ROLL A HUGE BOULDER UP A HILL, ONLY TO WATCH IT ROLL BACK DOWN, AND TO REPEAT THIS THROUGHOUT ETERNITY



A MORE MODERN VERSION OF THE « MYTH » OF SISYPHUS

HOW NOW, CAN IT BE THAT SISYPHEAN (NUCLEAR) ASTROPHYSICISTS DO EXIST??





Fig. 3. Snapshots of models W15-4 (left) and L15-3 (right) illustrating the four phases characterizing the evolution of our 3D models (see text for details). Each snapshot shows two surfaces of constant entropy marking the position of the shock wave (grey) and depicting the growth of non-radial structures (greenish). The time and linear scale are indicated for each snapshot.

THE ¹²C (α, γ) ¹⁶O RATE FROM SIMPLISTIC MODELS FOR THE EVOLUTION OF THE NUCLIDIC CONTENT OF THE GALAXY



BEWARE:

ALL PRE-SN STRUCTURES ADOPTED IN SN SIMULATIONS ARE WRONG!!!!

ONE CANNOT GET A SAFE AND MAGNIFICENT SN EXPLOSION USING A ROTTEN ONION AS A START!!



AN ARTIFICIALLY MODIFIED ONION IS USED INSTEAD IN ORDER TO START 2D-3D SN SIMULATIONS