computational astrophysics (@ Uchicago) in 2042
As you can see, by late next month you'll have over four dozen husbands. Better get a bulk rate on wedding cake.
As you can see, by late next month you'll have over four dozen husbands.

Hold on - shouldn't you be using more than two data points?
Special thanks to

Richard Miller

Peter Vandervoort
THE X- AND Y-FUNCTIONS FOR ISOtropic SCATTERING. I

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Received November 7, 1951

ABSTRACT

In this paper X- and Y-functions which occur in the solution of transfer problems in atmospheres of finite optical thicknesses and scattering radiation isotropically with an albedo \( \omega_0 \leq 1 \) for single scattering are tabulated.

The values of the albedo, \( \omega_0 \), and optical thickness, \( \tau \), for which solutions are tabulated are: \( \omega_0 = 1, 0.95, 0.9, 0.8, 0.5, \) and \( \tau = 0.05, 0.10, 0.15, 0.20, 0.25, 0.5, \) and 1.

1. Introduction.—In a series of papers published in this Journal during the years 1944–1949, it was shown how exact solutions for many of the standard problems in the theory of radiative transfer in plane-parallel atmospheres can be expressed in terms of certain H- or X- and Y-functions. The H-functions occur in the solution of problems in semi-infinite atmospheres, while the X- and Y-functions occur in the corresponding problems in atmospheres of finite optical thicknesses. This theory has since been systematically presented in S. Chandrasekhar's Radiative Transfer (Oxford: Clarendon Press, 1950). This book also includes tables of H-functions suitable for several problems in the theory of stellar and planetary atmospheres. But so far no similar tables of the X- and Y-functions have been available.

Now the X- and Y-functions are defined as solutions of the pair of integral equations,

\[
X(\mu) = 1 + \mu \int_0^1 \frac{\Psi(\mu')}{\mu + \mu'} [X(\mu) X(\mu') - Y(\mu) Y(\mu')] d\mu' \tag{1}
\]

and

\[
Y(\mu) = e^{-\tau/\mu} + \mu \int_0^1 \frac{\Psi(\mu')}{\mu - \mu'} [Y(\mu) X(\mu') - X(\mu) Y(\mu')] d\mu', \tag{2}
\]

Chandra and human computers
Fermi’s interest in computing: the Fermi-Pasta-Ulam problem

- Model of interactions of atoms in a crystal by a long 1d chain of masses connected by strings obeying Hooke’s law, but with a weak nonlinear term.

- Calculations done at T7 division led by Nick Metropolis on MANIAC 1 computer by Mary Tsingou.

- Calculations yielded a surprising result (the FPU paradox) that weak nonlinearity was not sufficient to reach equilibrium and equipartition of energy.

- First written-up as a Los Alamos report in May 1955, marked the beginning of both a new field, the non-linear physics, and the age of computer simulations of scientific problems.

- In the 1960s after follow-up investigations by Norman Zabusky and Martin Kruskal led to the development of concept of solitons.

Algorithm sketch by Mary Tsingou used to code the first FPU numerical calculation. Physics Today 2008.
Established in late 1950s and directed by Nick Metropolis (U.Chicago BS 1936, PhD 1941, research instructor 1942-42, Professor 1957-1965) who oversaw design and construction of MANIAC III at U.Chicago

Allowed Dick Miller to transition to computational astrophysics research and carry out some of the first direct N-body integrations of ~100 bodies, discovering the numerical “Miller instability” in the process (Miller 1964).

ON THE STABILITY OF A DISK GALAXY

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It is a pleasure to acknowledge the use of the Maniac III Computer, made available for these experiments by the Institute for Computer Research of the University of Chicago.
Numerical models of galactic dynamics

- First numerical galaxy models with spiral structure; indicated prevalence of two-armed spirals.

- Models of disk and rotating bar stability

A NUMERICAL EXPERIMENT ON THE EQUILIBRIUM AND STABILITY OF A ROTATING GALACTIC BAR

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Received 1982 January 4; accepted 1982 February 23
d) Summary and Analysis

The programs are designed, as was the ILLIAC program (Miller 1978), with heavy emphasis on motion pictures. At each integration step, coordinates of some 2000 particles are written into a picture file. These files provide large enough samples for numerical studies. In addition, some numerical properties are evaluated from the full set of particles as the

64^3 grid 10^5 particles

NUMERICAL EXPERIMENTS ON THE CLUSTERING OF GALAXIES

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ABSTRACT

Growth rates for disturbances that lead to galaxy clustering can be determined with a precision of 1–2% in numerical experiments. Rates determined experimentally are consistent and robust. Growth rates depend on various experimental conditions such as expanding (Ω = 1), nonexpanding, variations of parameters, etc., in the manner expected. The experiments reported here were designed to study the dominant physical processes of gravitational clustering in an expanding universe of conventional matter and are based on n-body integrations for 100,000 particles that respond self-consistently to forces of self-gravitation with periodic boundary conditions. Power spectral analysis provides the tool that permits growing disturbances to be analyzed with this accuracy.

Presently observed structure on the scale of galaxy clusters and superclusters is most easily described in terms of matter being swept away from growing empty regions. Galaxies pile up into clumps, with "strings" connecting neighboring clumps. The resulting structure has a cellular appearance that looks a good deal like the clustering observed on the scale of large voids and superclusters. Clustering on this scale develops naturally through dynamical processes, and it shows no tendency to saturate even beyond present-day strengths.
1980 Peebles’s letter to Dick Miller commenting on his structure formation simulations

Professor Dick Miller
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July 31, 1980

Dear Dick,

I quote Ed Gruch on your novel: “It really does look like the universe.”

I’m still worried about the rate of growth of the power spectrum at long wavelengths, and so maybe it would be good to compare notes on definitions and equations. The comoving coordinates $x = x^1, x^2, x^3$ have the range $0 < x^0 < 1$.

The Fourier transform of the particle distribution can be written as

$$\int_0^1 \frac{d^3k}{(2\pi)^3} \exp \left[ i \cdot \mathbf{k} \cdot \mathbf{x} \right] \rho(k),$$

where the sum is over the $N$ particle positions $\mathbf{x}_j$. Then for a random particle distribution, $|\rho(k)|^2 \sim N^{-1}$. A measure of the density fluctuations on scales $\zeta \times 10^n$

$$\frac{\delta \rho}{\rho} \sim \frac{1}{N} |\rho(k)|^2,$$

where the sum is over wave numbers $k \lesssim 10^n$. Where this sum to $k$ is small, and the growing mode dominates, I expect $|\rho(k)|^2 \sim k^{\gamma}$, and an disconnected by the discrepancy with your results.

I can’t check all of the difference scheme in your screen because you don’t seem to define $\rho_{(n)}$. I get

$$\rho_{(n+1)} = \rho_{(n)} - \frac{1}{2} \left[ \rho_{(n+1/2)} - \rho_{(n-1/2)} \right]$$

where

$$\rho_{(n+1/2)} = \int_{n/2}^{(n+1/2)} \rho(k) dk,$$

and

$$\rho_{(n-1/2)} = \int_{(n-1/2)}^{n/2} \rho(k) dk.$$

Please reply.

Kee.  

P.J.E. Peebles
Gift from the Andrews Foundation allowed department to purchase brand new DEC VAX server, which was the first oddjob.

Dave Arnett joined the faculty (1976-1989) and spearheaded research on numerical modelling of supernova explosions.
SUPERNOVAE AS PHENOMENA OF HIGH-ENERGY ASTROPHYSICS*

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INTRODUCTION

The concept “supernova” includes a number of different theoretical ideas and observationally distinct phenomena. The list includes extragalactic events,\textsuperscript{1,6} historical galactic events,\textsuperscript{14} (e.g., the Crab, Tycho and Kepler), “supernova remnants” (SNR),\textsuperscript{7,8} some black holes, and compact x-ray sources.\textsuperscript{9,12,13} Furthermore, supernovae are thought to be exploding stars, the accelerators of cosmic rays,\textsuperscript{14} the site of nucleosynthesis,\textsuperscript{15} and an important contributor to the heating and dynamics of the interstellar medium.\textsuperscript{16}

This diversity of attributes ascribed to supernovae underlines their importance to astrophysics, and also suggests the danger of their use as a \textit{deus ex machina} to clothe our ignorance. This problem can be avoided by testing theory with observation; this paper will discuss some observational consequences of theoretical ideas, emphasizing the newest developments and what currently seem to be the most fundamental aspects of the problem.
HERBIG-HARO OBJECTS AS THE HEADS OF RADIATIVE JETS

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ABSTRACT

The interpretation of certain Herbig-Haro (HH) objects as the heads of nonadiabatic supersonic jets is explored with the help of two-dimensional numerical simulations. It is found that, in addition to the basic two-shock morphology of adiabatic jet heads, radiative jets develop a dense shell between the jet shock and the leading bow shock when the cooling distance behind either one of these shocks is smaller than the jet radius. The shell is dynamically unstable and undergoes large structural variations on time scales as short as the gas flow time across the head. It is proposed that the radiatively cooling shell may account for the variable emission pattern from objects like HH 1. In particular, the distinct emission knots that are often detected in these sources could be identified with density inhomogeneities in the shell. It is suggested that HH objects with measured space velocities that exceed the spectrally inferred shock velocities could correspond to “heavy” jets (jet density greater than the ambient density) in which the bow shock is effectively adiabatic, and that low-excitation objects in which these two velocities are comparable may represent “light” jets where the jet shock is nonradiative.

Subject headings: hydrodynamics — nebulae: general — shock waves — stars: pre-main-sequence
Is the 1.5-ms pulsar a young neutron star?

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The 1.5-ms pulsar PSR1937+214 is an unusual object; its extremely short period and slow spin-down rate imply a magnetic field\(^1\) of \(4 \times 10^8\) G, much lower than that of a canonical pulsar. Contrary to previous models, we propose here, as an explanation for these properties, that PSR1937+214 is a young neutron star (consistent with a kinematic age of \(\sim 10^4\) yr) spun up by accretion from a high-mass companion in a close binary system. The supercritical mass transfer rates expected in such a binary system should allow the neutron star to be spun up in the comparatively short time of \(\sim 10^4\) yr. The accretion process will also power thermomagnetic effects that could remove the strong magnetic field of a young pulsar from the crust of the star in a similarly short timescale.
1998 FLASH center was established at the University of Chicago as a result of successful proposal to the DOE/ASC Academic Strategic Alliance Program under Advanced Scientific Computing Initiative (ASCI). The main goal was to develop a numerical tool to study astrophysical thermonuclear runaways (flashes).

Dave Arnett’s former postdoc, Bruce Fryxell, took an active role in the development of the FLASH code.

First version released in 2000. 4 major releases by 2015. Development continued ever since expanding capabilities, scope, and enabling numerical computations in several disciplines of physics and astrophysics both in academia and in government labs: supernova modelling, structure formation, combustion, turbulence, etc.
ALLA code: supernova and combustion modelling
galaxy and cluster formation modelling
FUTURE FORECASTS ("PROVOCATIONS")
and DISCUSSION
"We are probably nearing the limit of all we can know about astronomy." - Simon Newcomb, astronomer, 1888.

"The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote." - Albert A. Michelson, physicist, 1894 (the first head of Physics Dept. at U.Chicago)

"There is nothing new to be discovered in physics now; All that remains is more and more precise measurement." - Lord Kelvin, 1900.
FUTURE FORECASTS ("PROVOCATIONS")
and DISCUSSION
In 2042 code development will follow open source and crowd source models, harnessing citizen scientists fluent in computer science.

A lot of computational research will be towards building infrastructure, maximizing available manpower.

Teams that build large codes will be similar to teams that build large instruments and experiments (division of labor, etc.)
Provocation 1:

Astrophysicist-written code will be banned from running on supercomputers, because it will be too amateurish and wasteful of scarce computing cycles. Consequently, professional supercomputing programming support will be an essential personnel infrastructure for the future department, analogous to professional system and network admins today.

Provocation 2:

Computations will cease to be reproducible. Every supercomputer calculation will be associated with stochastic error bars. The output of computations will therefore increasingly mimic experimental measurements, and will have to be compared to experimental measurements in interesting, novel, and possibly scandalous ways.
Moore’s law

- What can one do with 1 yottaflop/s ($10^{24}$ ops/s)?
Galaxy formation: 3D galaxies in cosmological volumes
- $(100 \text{ Mpc})^3$ box
- $60,000^3$ particles (200 $M_\odot$ mass resolution)
- 30 pc spatial resolution

Star formation: Full galaxy simulation
- 0.1 pc cell, $100,000^3$ cells
- $(10 \text{kpc})^2 \times 100 \text{pc}$ box

Still need to wait another ~ 15 years for galaxy formation and star formation becoming one field.
HPC computations will not keep up with extrapolation of the Moore’s law past ~2020

By 2042 we will “solve” galaxy formation

Computation-intensive research in 2042 will be largely about shuffling and operating on bytes of data and not actual integer or floating point operations.
parallelism in the future will be handled by run-time systems and not explicitly by users.

The high-performance codes in 2042 will still be in Fortran (Fortran40?)
In the next 25 years, I expect continued advances in computational modeling of galaxy clusters in terms of both physical modeling as well as the spatial and mass resolution, which should enable us to study the distributions of dark matter, gas, and stars in clusters on scales less than 1kpc. This will enable us to study evolution of galaxies in clusters as well as interactions of their dark matter, gas, and stellar components in unprecedented detail.

Given that the ab-initio modeling of all relevant baryonic physics will likely remain out of reach (even by 2042), I expect that advances in this field will likely come from (1) improvements in sub-grid modeling of relevant astrophysical processes through detailed comparisons of simulations and observations and (2) development of techniques (e.g., increasingly more robust mass proxies) for cosmological applications.
In the last 25 years, computational fluid dynamics advanced at an exceedingly rapid pace. 25 years from now? We can only extrapolate on trends. If you are interested in FV/FD methods and multi-physics codes that can run _efficiently_ on leadership HPC facilities (as opposed to just heating up the room), you don’t like what you see hardware-wise: flop is king and memory is shriveling and becoming exceedingly slow. What do we do?

We adapt, with commitment to code and algorithm development (not the kind your physics grad student and 2-year postdoc can do). Future multi-physics HPC codes will be flexible and hybrid, allowing different physical treatments that actually take advantage of on-node accelerators and many-core architectures – kinetic ions and fluid gyrokinetic electrons; MHD fluid plus kinetic energetic species and so on. Incremental changes won’t cut it. A couple of OpenMP directives won’t do the trick. Who knows, in 25 years we may even have exascale – and be able to use it!
Provocation 1: Computational hardware development is driven by mass-market forces -- Intel, NVidia, IBM et al. care about selling to large corporate customers and the mass public, not so much to scientists.

This will lead to decreased performance of scientific high-performance computations.

The number of astrophysical applications that are appropriate for supercomputer solutions will narrow considerably. And the affliction will to some extent be felt up and down the hardware scale, from supercomputers to cell phones, since they all will use rather similar hardware.
Future computers will require ~10s of Megawatts of electric power, which is a significant fraction of the power capacity of a nuclear reactor. Computations will be expensive!

I am pretty sure that people will find a way to burn the cycles. What I am not sure about whether they will find a way to get good science out of them…
“If enough people predict something, it won’t happen.”
- J.G. Ballard (British writer, specializing in apocalyptic novels)
THE FERMIAC

The Monte Carlo trolley, or FERMIAC, was invented by Enrico Fermi and constructed by Percy King. The drums on the trolley were set according to the material being traversed and a random choice between fast and slow neutrons. Another random digit was used to determine the direction of motion, and a third was selected to give the distance to the next collision. The trolley was then operated by moving it across a two-dimensional scale drawing of the nuclear device or reactor assembly being studied. The trolley drew a path as it rolled, stopping for changes in drum settings whenever a material boundary was crossed. This infant computer was used for about two years to determine, among other things, the change in neutron population with time in numerous types of nuclear systems.