HOW TO MODEL THE CHEMICAL EVOLUTION OF GALAXIES

JOACHIM KÖPPEN
Institut für Theoretische Physik und Sternwarte, Olshausenstr. 40, D-W-2300 Kiel, F.R.G.

1. The First Glimpse: The Simple Model

For a first interpretation of the comparison of observational data, the crude "Simple Model" of chemical evolution is quite useful. Since it has well been described in the literature (e.g. Pagel and Patchett 1975, Tinsley 1980), let us here just review the assumptions and whether they are satisfied:

1. The galaxy is a closed system, with no exchange of matter with its surroundings: For the solar neighbourhood this probably is not true (the infamous G-dwarf-"problem", Pagel 1989b). For the Magellanic Clouds this is most certainly wrong, because of the presence of the Inter-Cloud Region and the Magellanic Stream, and evidence for interaction with each other and the Galaxy as well (cf. e.g. Westerlund 1990).
2. It initially consists entirely of gas (without loss of generality of primordial composition): This is good approximation also for models with gas infall, as long as the infall occurs with a time scale shorter than the star formation time scale.
3. The metal production of the average stellar generation (the yield y) is constant with time: Initially, it is reasonable to make this assumption. For tables of the oxygen yield see Köppen and Arimoto (1991).
4. The metal rich gas ejected by the stars is completely mixed with the ambient gas. To neglect the finite stellar life times ("instantaneous recycling approximation") is appropriate for elements synthesized in stars whose life time is much shorter than the star formation time scale, such as oxygen, neon, sulphur, and argon.
5. The gas is well mixed at all times: We don't know. The dispersion of H II region abundances may give an indication. In the Magellanic Clouds Dufour (1984) finds quite a low value (±0.08 dex for oyxgen).

Then the metallicity Z of a primarily produced element (such as O, Ne, S, Ar) at every time t is a simple function of the gas fraction (by mass) f_g at that moment:

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$$Z(t) = y \ln(1/f_g(t)) \quad (1)$$

where stellar nucleosynthesis, evolution, and the initial mass function all are concentrated into a **single** number (the yield y). The (hydro)dynamic evolution of the galaxy and its star formation history are described **separately** by the 'astration parameter' $\ln(1/f_g)$, also a **single** number. Note that the metallicity does not depend on the actual temporal history of the star formation rate (how complicated it may be) or on its dependence on the gas fraction. Also, the metallicity is always proportional to the yield of the stellar population, and thus, in the same galaxy, the abundance ratios essentially give information on stellar nucleosynthesis!

2. A panorama of types of chemical models

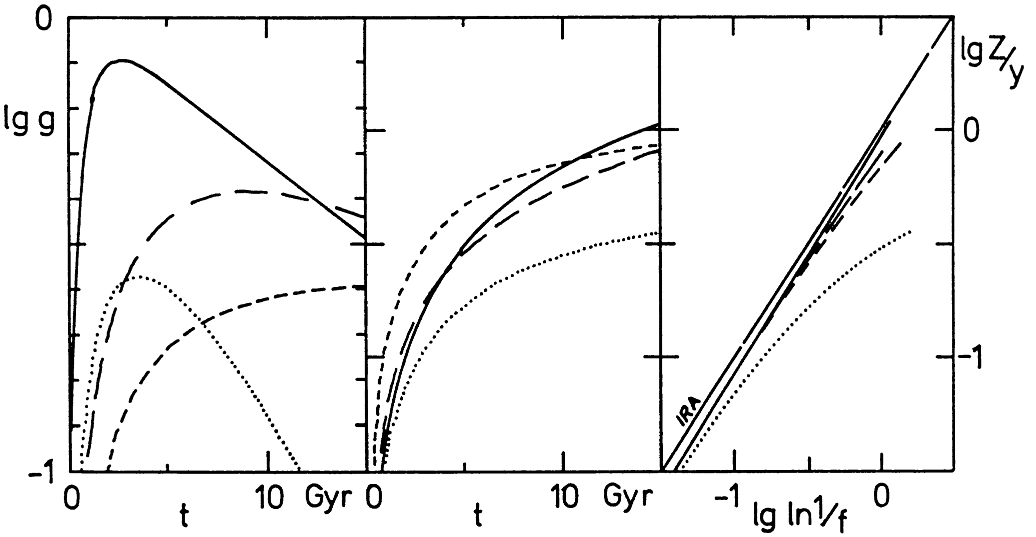

Fig. 1. Chemical evolution of infall models: time evolution of gas density g, metallicity Z, and the $\lg Z$ vs. $\lg \ln(1/f_g)$ diagram for models with yield 1, a star formation rate proportional to g. An approximative treatment of finite stellar lifetimes is used. If they are neglected, the line labelled IRA is obtained. Infall time scales are $0.1\,\tau_{\mathrm{SFR}}$ (full lines), $0.7\,\tau_{\mathrm{SFR}}$ (long dashes) and $50\,\tau_{\mathrm{SFR}}$ (short dashes). Also shown (dots) is a model with continuous galactic wind (mass loss rate = 3*SFR).

In the following let's look at various types of chemical evolution models: Fig. 1 shows the temporal evolution of the gas density g and metallicity Z and the $\lg Z$ vs. $\lg \ln(1/f_g)$ diagram for models with exponential infall of zero metallicity gas. If

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infall occurs quickly — i.e. with a time scale shorter than for star formation — one essentially gets the "closed-box" Simple Model. We note that in the metallicity-gas fraction diagram this corresponds to a straight line of slope 1. All models were computed with an approximate treatment of the finite stellar lifetimes, and so avoid the "instantaneous recycling approximation", but as can be seen in the figure, this only leads to a fairly small (less than 0.1 dex) deviation from Eq. 1. Infall gives rise to lower metallicities, i.e. a lower effective yield

$$y_{\rm eff} = Z/\ln(1/f_g) \qquad (2)$$

but this is only noticeable with very slow infall at large ages. So, in a way, all these models — despite their rather different evolution of gas density or metallicity — behave very closely as a Simple Model.

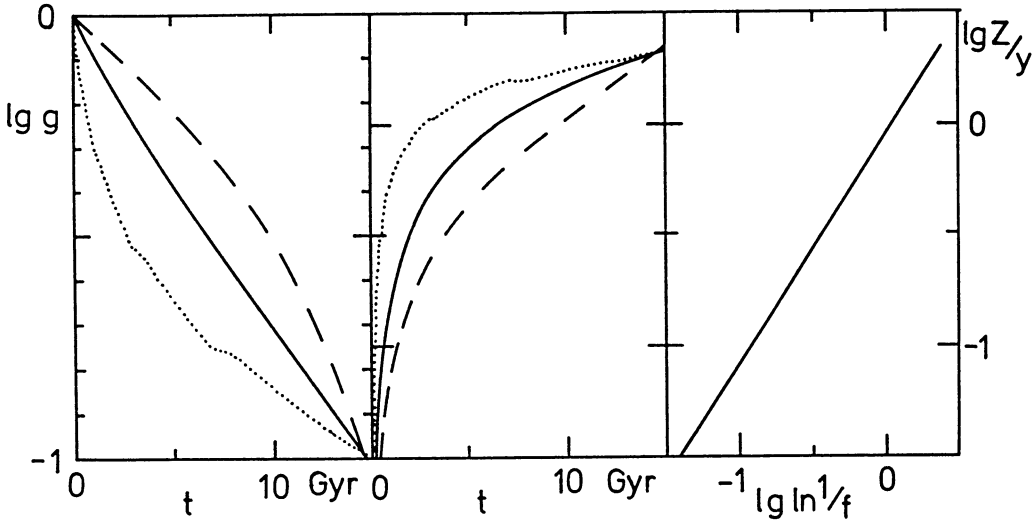

Fig. 2. Chemical evolution of the Simple Model with different dependences of the star formation rate on gas density g: linear (full line), $g^{0.25}$ (dashed), and quadratic (dotted). The constant of proportionality is adjusted to give the same gas density ($g = 0.1$) after 15 Gyr. The kinks in the dotted curves as due to our representing the spectrum of stellar lifetimes by only 5 values.

The exact dependence of the star formation rate on the gas density, if it exists at all, is unknown. The previous models were done with a linear dependence. In Fig. 2 we see that this dependence may alter the gas density evolution and thus the star formation history, and the age-metallicity relation, but no change at all is seen in the Z vs. f_g diagram.

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That star formation must be a simple function of time is not a necessity of the physics of galaxies, but rather a simplifying assumption to compute models. For irregular galaxies the idea of stochastical self-propagating star formation (SSPSF, Gerola et al. 1980) is often discussed: star formation may be induced in the vicinity of previous star formation activity. This gives rise to a strongly fluctuating star formation rate. Similar fluctuations are also possible due to the nonlinear behaviour of the equations for the evolution of interstellar clouds (Struck-Marcell and Scalo 1987), or of the energy balance in detailed multi-phase models of the interstellar medium (Theis et al. 1992). Matteucci and Chiosi (1983) simulated the SSPSF process by computing the chemical evolution of models with a rapidly fluctuating star formation rate. Since perfect mixing in the interstellar medium is assumed, the abundance of oxygen is still closely linked to the gas fraction as in a Simple Model (see our Fig. 3 and their Fig. 8).

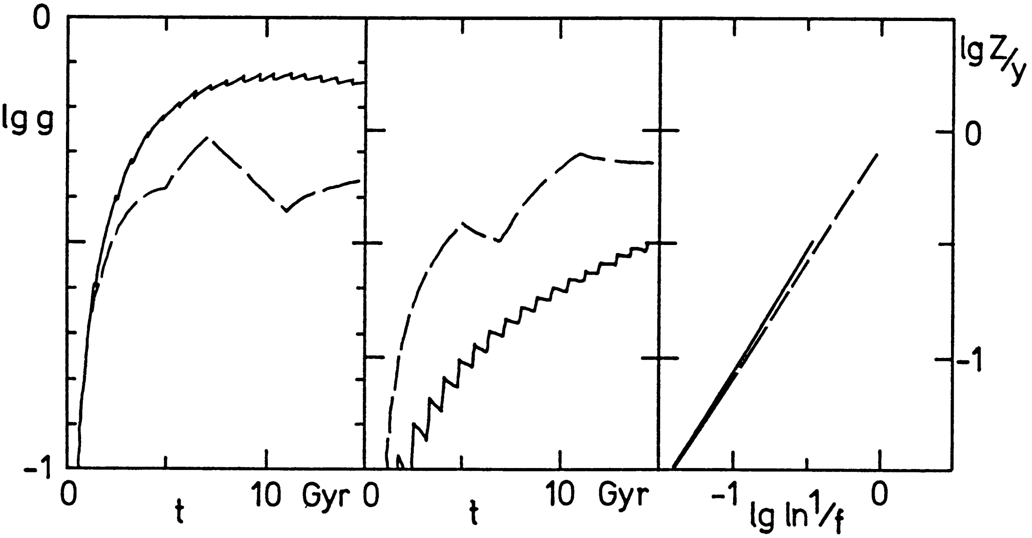

Fig. 3. Chemical evolution of models with very short star formation bursts every 1 Gyr (full line) and long ones (from 1 ... 5 and 7 ... 11 Gyr; dashed line).

However, these simulations are rather simplified: They do not take into account the multi-phase structure of the ISM (and thus the various delay times of mixing and enrichment). Also, they assume that chemical enrichment is a purely local process: gas flows in e.g. the hot phase, distribution of metals over a finite volume by galactic fountains, etc. are ignored. Calculations of the evolution with incomplete mixing (Wilmes and Köppen 1991) show that non-local effects do not affect the average

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abundance values, but the correlation between secondary and primary elements (e.g. N/O ratio).

Many galaxies are not isolated: The Magellanic Clouds are connected with the Inter-Cloud Region consisting of gas and embedded stars, which contains as much H I gas as the SMC. The Magellanic Stream forms a long, gaseous tail to the Clouds, and is regarded as an indication of global interaction in the Magellanic system (Wayte 1990).

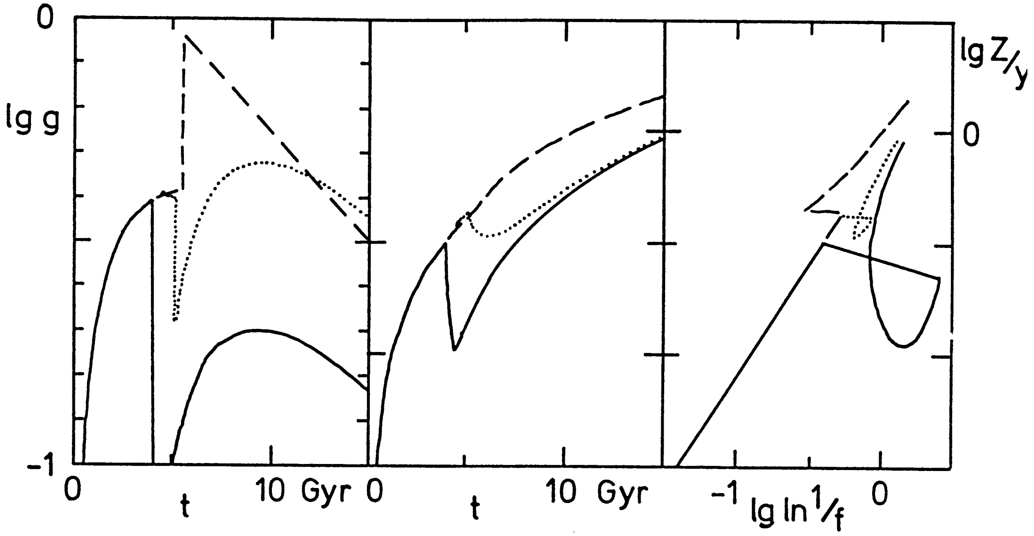

Fig. 4. Effects of possible processes caused by galactic interactions: sudden 99 percent gas loss at 4 Gyr (full lines), sudden gas inflow (of additional 50 percent mass) at 6 Gyr (dashes), star burst (3*SFR) at 4.5 Gyr and 50 percent gas loss at 5 Gyr followed by this gas flowing back with time scale 1 Gyr (dots).

What could happen during an interaction? While we do not claim to produce a physically consistent list of processes and event, let us consider the effects of the following items on chemical evolution (as shown in Fig. 4):

1. Sudden gas loss by tidal interaction: Within a few Gyr the gas that had been bound in stars of intermediate life time (and low metal production) is released and — depending on the IMF — a fair fraction of the lost gas is replenished, the metallicity drops. If star formation continues, the system recovers to an almost normal Simple Model after few $\tau_{\rm SFR}$ (full lines).
2. Sudden inflow of gas or loss of stars: Both processes increase the gas fraction for some time. After few $\tau_{\rm SFR}$ the model evolves again as a Simple Model (dashed lines).

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3. Partial exchange of mass: Combination of the previous two events.
4. Star formation burst: The effects can be seen in Fig. 3: a quick increase of the metallicity followed by a decrease when the intermediate mass stars die. Essentially like a Simple Model.
5. SN-driven galactic wind following an intense starburst: The dotted curves in Fig. 4 show that the evolution is dominated by the gas loss effects.

Thus, substantial deviations from the Simple Model can only be caused by really drastic changes in the parameters.

Pure chemical evolution has one weak spot: one can only determine the "chemical age" of a system, not the absolute one: e.g. the more gas-rich SMC could be a galaxy genuinely younger than the more metal-rich LMC, if they had a similar star formation time scale. On the other hand, it could be of the same age, but with a lower star formation time scale.

3. Observational constraints

If one wants to make a chemical evolution model for a galaxy, what observational constraints are valuable?

- Present metallicity: this can be obtained from H II region and SNR emission line spectra. While one gets e.g. the oxygen abundance, the iron abundance — so often taken as a metallicity indicator from stellar photometry and spectra — cannot be obtained, because of weakness or lack of suitable lines, poorly known collisional rates, and probable lock-up into dust grains.
- Present gas fraction: the neutral gas mass comes from H I measurements; molecular mass could be estimated from CO. For the galaxy's total mass which takes part in the chemical evolution, one often uses the dynamical mass (from the velocity dispersion seen in the H I 21 cm line widths). This is a problematic approach, since this could well be affected by dark matter. Ideally, one should use the total mass in gas and stars. The latter is obtained from the absolute luminosity of the stars by using stellar population models, thus it is model-dependent. A grid of Simple Models can be found in Arimoto and Tarrab (1990) who also compute the photometric colours.

These two data may already tell important things: Pagel et al. (1978) find that that the average oxygen abundances of both Magellanic Clouds can well be explained with a simple model with the **same** metal yield $y = 0.003 = 0.15\,Z_\odot$ (it is also compatible with regions in M 33 and M 101). This model also explains the chemical compositions and gas fractions of 6 irregular and blue compact galaxies (Lequeux et al. 1979).

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- Age metallicity relation: This is a more powerful constraint to distinguish between different model types (see our figures). However it is very difficult to obtain, since both metallicities and ages must be derived (cf. Twarog 1980). In the Magellanic Clouds the use of the star clusters does not seem to be a proper way (Richtler 1992).
- Stellar metallicity distribution function: This involves only the determination of metallicity, but in a statistically complete sample of stars of the same type (G-dwarfs in the solar neighbourhood (Pagel and Patchett 1975, Pagel 1989b), K-giants in the Bulge (Rich 1988)). If known, this function is an extremely useful constraint on infall (e.g. Köppen and Arimoto 1990a,b).
- Photometric colours: Since the colours are sensitive to the ratio of present and past integrated star formation rate (e.g. Searle et al. 1973, Rocca-Volmerange et al. 1981), they can help to fix the star formation history, however, not in great detail, especially in the far past.
- Abundances from planetary nebulae: with planetaries one can probe into the past (as with stars), and also take advantage of the better abundance diagnostics by emission lines. The difference of mean abundances of planetaries and H II regions gives some constraints on the age-metallicity relation. Of course, several problems remain: accurate abundances, determination of ages, spatial dispersion of the star from its place of birth ought to be mentioned.

4. Abundance gradients in spiral galaxies

The trouble with abundances gradients seen with H II regions is that there are far too many theories to explain them (Pagel 1989a, Götz and Köppen 1992): radial variations of the yield or of the star formation rate, various forms of gas infall, including a radial variation of the infall time scale, radial gas flows in the disk (caused by various ways). This ambiguity may be resolved by looking at the temporal evolution of the gradients: Here one can distinguish between different models (Köppen 1992), and the information about the gradient, say at about 10 Gyr, would be very helpful to put constraints on the star formation rate and on dynamical processes (infall, radial flows). Planetaries may be very useful here (see Maciel and Köppen, this conference).

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SMOTCH - Simple MOdel waTCH

The dedicated hardware solution for DIY chemical evolution of galaxies

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The three scales near the bottom solve the basic equation of the Simple Model of chemical evolution $Z = y \ln(1/f_g)$, in convenient units and with proper yields y:

- **Gas fraction** (`fixed` scale) is read off or set at the pointer (`moving` black triangle). Note: if the gas fraction is below about 10 percent, a large portion of the gas is returned with appreciable delay times by intermediate mass stars. Thus, the Simple Model can no longer give correct results.
- Exponent for power law **IMF**s (`fixed` scale) (Salpeter: 1.35, marked by **S**) and a mass range from 0.05 to 60 $M_\odot$. This is basically the oxygen yield, as computed by Köppen and Arimoto (1991) A&A Suppl. **87**, 109 and **89**, 420:
  - The actual yield can be read from the `moving` abundance scale, when the dial is set in the position as shown (gas fraction 37%): so an IMF with a slope of 2.0 gives an oxygen yield of $\lg y/Z_\odot = -1.35$ dex.
  - The outer `fixed` scales $\mathbf{M}_u$ and $\mathbf{M}_\ell$ indicate how the yield changes, if upper and lower mass limits are varied: e.g. using $M_u = 100\ M_\odot$ raises the yield by 0.2 dex. Using also $M_\ell = 0.2\ M_\odot$ gives a further increase by 0.4 dex.
  - The yields of the IMFs of Tinsley (**T**), Miller/Scalo (**MS**), and Scalo (**Sc**) are marked, with the original mass ranges given by the authors.
- The gas **metallicity** $\lg Z/Z_\odot$ (`moving`) is found opposite the selected value of the IMF. Note that this is exact only for O^{16}; all other 'metals' are O.K. within ±0.5 dex (except He and secondary nuclei such as C^{13} and N^{14}).

Any of the three quantities can be computed from the other two: Given a gas faction, the metallicity can be read off for any yield (IMF), or the yield is obtained from an observed Z. Likewise, any combination of IMF and Z gives the gas fraction.

IF one makes the additional assumption of a linear star formation law $SFR = f_g/\tau_{\rm SFR}$, one can estimate the actual age of a galaxy or the star formation time scale $\tau_{\rm SFR}$. This is done with the top supplementary scales which solve $f_g(t) = \exp(-\alpha t/\tau_{\rm SFR})$. The locked-up mass fraction α depends only weakly on the IMF.

- **Time** t (`fixed` scale) in Gyr. The black dot marks 15 Gyr.
- **Star formation timescale** $\tau_{\rm SFR}$ (`moving` scale) in Gyr. The solar symbol (at 5 Gyr) indicates a reasonable value for the solar neighbourhood: the gas fraction after 15 Gyr would be 2%. Since the gas is depleted more slowly by the factor $1/\alpha$ (the `moving` short scale **IMF** gives ≈ 0.2 dex for Salpeter IMF), the true gas fraction is higher (10%). For steep IMFs, this correction is rather small.

Note that these top scales assume a specific SFR-law. However, for other laws, they can be used as a guideline.

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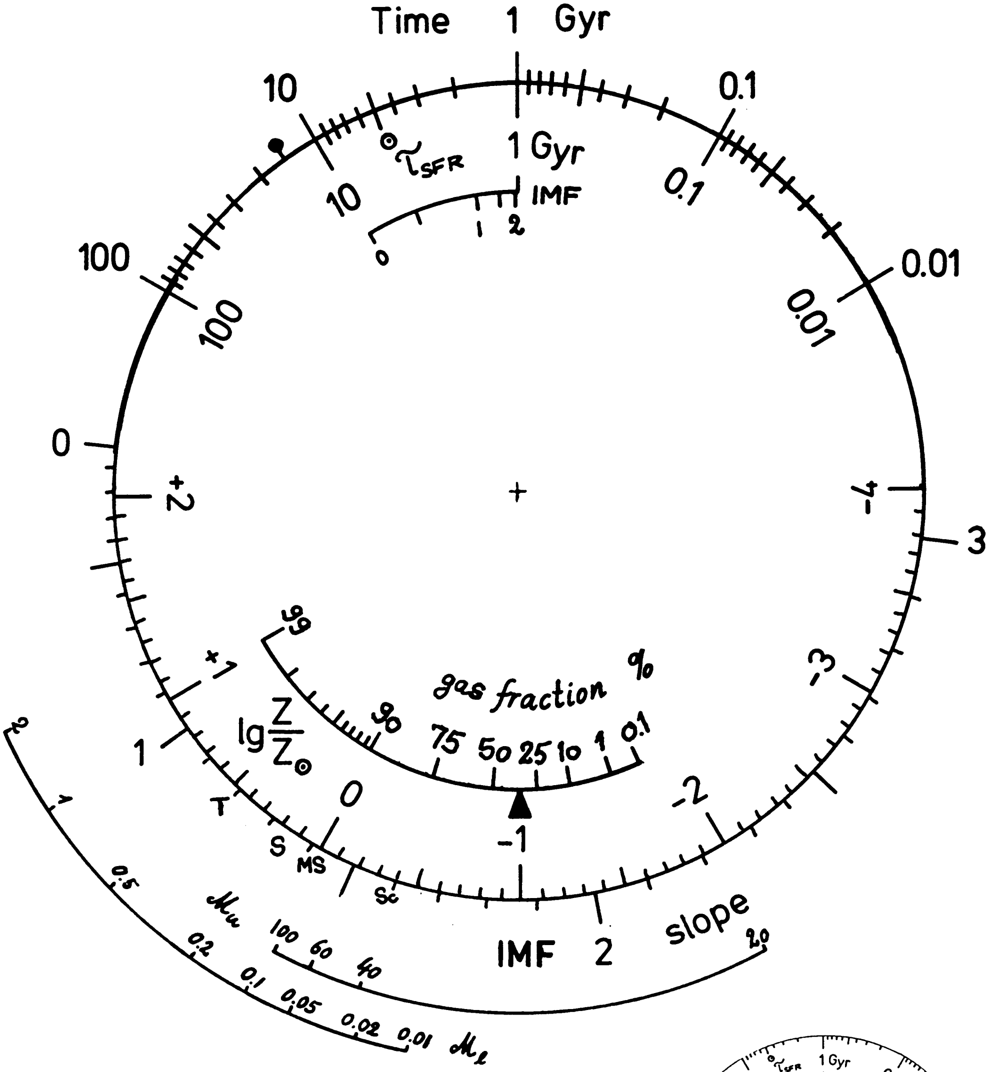

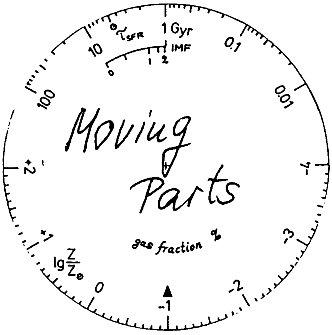

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