A Appendix

Many professionals may value equity options such as those purchased by Cephalon with the Black-Scholes/Merton model. Valuation using this model was presented in the text. However, a number of contractual features of the Cephalon options as well as the particular situation of the firm result in the Black-Scholes/Merton model being inappropriate in this situation. In order to more correctly value these options, we develop and estimate a GARCH-Jump option pricing model for the underlying stochastic process which includes features such as accretion effects and path-dependency of the contractual provisions. This model relaxes several of the assumptions in the Black-Scholes/Merton model, which allows for better modelling of several contractual features of the options.

First, the claims give Cephalon the unusual ability to buy an option on its own stock. Thus, these claims are in fact warrants.[1] However, since the warrants are owned by Cephalon, the dilution effect typically caused by exercising warrants works in the reverse direction here, and therefore, must be modeled implicitly. With more and more firms transacting in derivatives on their own stock, the modelling used in this paper should see wide applicability.

Second, a lognormal distribution is a poor descriptor of the conditional distribution of Cephalon's stock price. This is easily seen from recent historical data on Cephalon's stock. The stock price displays both skewness and excess kurtosis. To accomodate these patterns, we use a stochastic volatility process for the stock price. This immediately brings up the issue of estimation, which is not trivial for stochastic volatility models. To simplify the estimation problem we calculate the discrete-time GARCH process that converges to the stochastic volatility model, similar to Nelson (1990), and then estimate this GARCH process.

In addition to stochastic volatility, we need to incorporate the fact that a jump event will affect the stock price during the life of the options. This event (the FDA announcement) will have a substantial impact on the stock price. A jump process such as that used in Merton (1976) cannot be used here because the jump will occur on a known date, though with an unknown direction and

[1] Several papers have dealt with the topic of warrant pricing. Examples include Schwartz (1977) and Constantinides (1984). For this paper, we utilize the simple approach of Galai & Schneller (1978). Crouhy & Galai (1994) and Schulz & Trautmann (1994) examine a more accurate valuation technique that accounts for the leverage in a firm.

magnitude. To account for these features, the stock process is modeled using a GARCH-Jump process where the jump is a one-point jump. This model may be used to price options on any security where the underlying stock will be hit by a jump at a known date, though of unknown magnitude and direction. Examples include options on firms that are scheduled to make a public annonucement, firms in the midst of major litigation where it is known that a judgement will be made within a narrow time frame, or firms in the middle of merger negotiations, where again, the results will be announced within a narrow time frame.

Third, the options are path-dependent in that the value of the options at expiration depends on the average of the stock price over the month preceding the expiration date. All of these features could contribute substantially to the price of the Cephalon warrants, and each needs to be incorporated into any valuation model.

A.1 Time-Varying Volatility

The pricing of these warrants depends critically on the conditional distribution of Cephalon's stock price. As mentioned above, under the commonly-used assumption in Black-Scholes/Merton that the stock price follows a geometric Brownian motion process

$$\frac{dS}{S} = \mu\, dt + \sigma\, dW_t \tag{1}$$

where μ and σ are constants, W_t is a Wiener process, and the stock's conditional distribution is lognormal. However, if (1) is estimated for Cephalon's stock, an inspection of the residuals from the estimation shows that the assumption of normality is strongly violated. From January 1996 to May of 1997, the skewness of Cephalons daily log stock returns is -1.13 with a standard error of .26, while the kurtosis is 15.54 with a standard error of .13. These values are significantly different from that expected for a normal distribution. A more formal goodness-of-fit test for normality can be conducted using the Kolmogorov-Smirnoff D-statistic. This statistic yields a value of .49 for the log stock returns, while the 1% critical value for the test is .087. Thus, the test strongly rejects the null hypothesis of normality in the log returns.

To account for this non-lognormality in Cephalon's stock returns, we would like to incorporate stochastic volatiliy using the process

$$\begin{aligned} \frac{dS}{S} &= (a_0 + a_1\sigma_t^2)\,dt + \sigma_t\,dW_s \\ d\sigma_t^2 &= b_0(b_1 - \sigma_t^2)\,dt + b_2\sigma_t^2\,dW_\sigma \end{aligned} \tag{2}$$

where a_0, a_1, b_0, b_1, and b_2 represent constants, and W_σ is a Wiener process that has a constant correlation ρ with W_s. Due to the stochastic nature of the volatility process, this model exhibits excess kurtosis. In addition, depending on the sign of the correlation between the Wiener processes, the model can also display positive or negative skewness. The other assumptions implicit in the model above, such as mean-reverting volatility and volatility impacting the stock return's drift, are based on empirically observed characteristics common to a wide cross-section of stocks. Thus, the model in (2) is capable of displaying the key patterns of non-lognormality observed in Cephalon's stock price.

Howeve,r stochastic volatility processes of this form are extremely difficult to estimate. Common techniques used have included GMM (and EMM), Kalman filtering, simulated maximum likelihood, and Bayesian estimation.[2] The choice between these usually becomes a tradeoff between accuracy and computation time.

We approach this estimation problem in a slightly different manner. Instead of modifying the estimation technique, we will instead modify the stochastic process so that it is easy to estimate and then rely on convergence theory to obtain reliable estimates and prices. To this end, we instead modify the basic geometric process above to incorporate a time-varying volatility that is conditionally deterministic. The model that is used to accomplish this is the GJR GARCH(1,1)-in-mean model first introduced in Glosten, Jagannathan, & Runkle (1993).

$$\begin{aligned} \ln\frac{S_{t+1}}{S_t} &= \alpha_0 + \alpha_1\sigma_t^2 + \sigma_t\varepsilon_{t+1} \\ \sigma_t^2 &= \beta_0 + \beta_1\sigma_{t-1}^2 + \beta_2\sigma_{t-1}^2\max(0,-\varepsilon_t)^2 + \beta_3\sigma_{t-1}^2\varepsilon_t^2 \end{aligned} \tag{3}$$

Since the GARCH model has a time-varying volatility process, it is capable of displaying the kind of excess kurtosis found in the Cephalons returns.

[2]See Melino & Turnbull (1990), Gallant, Hsieh, & Tauchen (1994), Harvey, Ruiz, & Shephard (1994), Danielsson (1994), and Jacquier, Polson, & Rossi (1994) for examples of these estimation methods in the context of stochastic volatility models.

The GJR GARCH(1,1) model differs from the standard GARCH(1,1) model due to the addition of the term $\beta_2\sigma_{t-1}^2 \max(0, -\varepsilon_t)^2$. This term allows for asymmetric volatility shocks, i.e., negative shocks tend to increase volatility more than positive shocks. This allows us to capture the leverage effect that has been observed in stock market data by Black (1976) and many others. This asymmetric volatility impact causes the conditional distribution in the GJR GARCH model to display skewness. Finally, by adding a variance term, $\alpha_1\sigma_t^2$, to the return process, we allow for a time-varying mean as well. The conditional mean in this case is linear in the conditional variance.

Even though the GARCH model above incorporates the non-normal features we observe in Cephalon's returns, we need to show that the GARCH model approximates some form of the stochastic volatility model posed above. To do this, we informally derive the continuous-time limit of the GARCH process.[3] Since we will be taking the limit as the time interval shrinks, we will rewrite the GARCH process in a way such that it explicitly accounts for the length of the time interval and such that the limiting drifts and diffusions of the continuous-time processes exist.

$$\begin{aligned}\ln\frac{S_{t+h}}{S_t} &= \alpha_0 h + \alpha_1\sigma_t^2 h + \sigma_t\sqrt{h}\varepsilon_{t+1}\\ \sigma_t^2 &= \beta_0 h + \beta_1\sigma_{t-h}^2 h + \beta_2\sigma_{t-h}^2 h\max(0,-\varepsilon_t)^2 + \beta_3\sigma_{t-h}^2 h\varepsilon_t^2 \end{aligned}\tag{4}$$

where h is the time interval. Therefore, the trading period, T, is split up into $\frac{T}{h} = n$ trading intervals. With this definition, the conditional means and variances of the two processes can be calculated. The conditional means are given by

$$\begin{aligned}E_t[\ln S_{t+h} - \ln S_t] &= (\alpha_0 + \alpha_1\sigma_t^2)h\\ E_t[\sigma_t^2 - \sigma_{t-h}^2] &= [\beta_0 + (\beta_1 + \frac{1}{2}\beta_2 + \beta_3 - 1)\sigma_{t-h}^2]h\end{aligned}$$

while the conditional variances and covariance are given by

$$\begin{aligned}V_t[\ln S_{t+h} - \ln S_t] &= \sigma_t^2 h\\ V_t[\sigma_t^2 - \sigma_{t-h}^2] &= (\frac{1}{4}\beta_2^2 + 2\beta_2\beta_3 + \frac{1}{2}\beta_3^2)\sigma_{t-h}^4 h\\ Cov[(\ln S_{t+h} - \ln S_t)(\sigma_t^2 - \sigma_{t-h}^2)] &= -\frac{2}{\sqrt{2\pi}}\beta_2\sigma_{t-h}^3\end{aligned}$$

[3]See Nelson (1990) for a formal derivation for ARCH processes.

Therefore, as we take the limit as $h \to 0$ of (4), we get the following continuous-time process.

$$\frac{dS_t}{S_t} = [a_0 + a_1\sigma_t^2]\,dt + \sigma_t\,dW_S$$
$$d\sigma_t^2 = b_0[b_1 - \sigma_{t-h}^2]\,dt + \sigma_t^2\sqrt{\frac{1}{4}\beta_2^2 + 2\beta_2\beta_3 + \frac{1}{2}\beta_3^2}dW_\sigma$$

where

$$a_0 = \alpha_0$$
$$a_1 = \alpha_1 + \frac{1}{2}$$
$$b_0 = 1 - \beta_1 - \frac{1}{2}\beta_2 - \beta_3$$
$$b_1 = \frac{\beta_0}{1 - \beta_1 - \frac{1}{2}\beta_2 - \beta_3}$$
$$b_2 = \sqrt{\frac{1}{4}\beta_2^2 + 2\beta_2\beta_3 + \frac{1}{2}\beta_3^2}$$

and W_S and W_σ are Wiener processes with a constant correlation ρ given by

$$\rho = -\frac{2\beta_2}{\sqrt{2\pi\left(\frac{1}{4}\beta_2^2 + 2\beta_2\beta_3 + \frac{1}{2}\beta_3^2\right)}}$$

Thus, the continuous-time GJR GARCH(1,1)-in-mean process for the stock converges in distribution to the stochastic volatility process given in (2). Therefore, while the 1-period ahead conditional volatility in this GARCH model is deterministic, prices under this model converge to prices for the purely stochastic volatilty model in (2) as the time interval becomes small. Therefore, the prices of any European contingent claims written on a stock governed by these GARCH dynamics converge in distribution to the prices of similar claims written on the continuous-time stochastic volatility process. For daily data, these price differences will be insignificant.

Parameter estimates for the GARCH model using Cephalon's daily stock returns from January 1996 to May 1997 are given in Table 7. Most of the volatility parameters are found to be statistically significant indicating the appropriateness of the GARCH model. In addition, the Kolmogorov-Smirnov D-statistic drops to .07 on the residuals, indicating that the residuals display a much better fit with a normal distribution. The hypothesis of normality can no longer be rejected at the 1% level as before.

A.2 Risk-Neutral GJR GARCH Process

In order to price the Cephalon warrants, the stochastic process for the stock must be derived under the martingale measure, $\tilde{P}$, given that under the actual measure, P, it is governed by the GJR GARCH(1,1)-M process.[4] One consequence of using a GARCH model for the underlying stock price process is that the pricing of contingent claims is no longer preference-free. Therefore, we start off by defining the pricing kernel.[5] Let ξ_t represent the pricing kernel in the economy. The pricing kernel simply represents the intertemporal marginal rate of substitution in an economy. The evolution of the pricing kernel are defined as follows:

$$\frac{\xi_{t+1}}{\xi_t} = \exp\left[-r - \frac{1}{2}\phi_{t+1}^2 - \phi_{t+1}\varepsilon_{t+1}\right] \tag{5}$$

The variable ϕ_t is a time-varying function that determines the market price of risk in the economy. ϕ_t is determined as a result of equilibrium given a set of supply and demand functions in an economy. If ϕ_t is known, then the Radon-Nikodym theorem may be used to determine the martingale measure in the economy. Suppose that agents' beliefs in the econmy is captured by the probability space $(\Omega, \mathcal{F}, P)$ and $\omega \in \Omega$. Then martingale measure, $\tilde{P}$, is related to P by

$$\tilde{P}(A) = \sum_{\Omega} 1_{\{\omega \in A\}} \eta_t P(\Delta\omega)$$

where the Radon-Nikodym derivative η_t is given by the expression

$$\eta_T = \exp\left[\sum_{t=0}^{T} -\frac{1}{2}\phi_{t+1}^2 - \phi_{t+1}\varepsilon_{t+1}\right] \qquad A \in \mathcal{F}$$

[4] Amin & Ng (1993) studies the risk neutral process for an ARCH stock price process while Duan (1995) analyzes the risk neutral process for a GARCH(p,q) process.

[5] The pricing kernel, or marginal rate of substitution, is needed here because we are undertaking an equilibrium pricing model in an incomplete market. An alternative to this approach is the no-arbitrage model which attempts to match a cross-section of option prices (see, for example, Rubinstein (1994), Derman & Kani (1994), or Dupire (1994)). For the no-arbitrage approach to work well, however, a sufficiently large cross-section of options maturing on the same date is necessary. Such a cross-section is not available on Cephalon stock.

Because ξ_t represents the marginal rate of substitution in the economy, the price at time t of a stock is related to the time $t+1$ price of the stock by the standard Euler condition

$$S_t = E_t[\frac{\xi_{t+1}}{\xi_t} S_{t+1}]$$

where the expectation is taken with respect to the P measure. Substituting from (3) and (5), we can derive the market price of risk, ϕ_t, in terms of the parameters of the stock process.

$$\phi_t = \frac{\alpha_0 + (\alpha_1 + \frac{1}{2})\sigma_t^2 - r}{\sigma_t} \tag{6}$$

Now, we can use a discrete-time version of Girsanov's theorem to relate a sequence of standard normal random variables under the $\tilde{P}$ measure to a set under the P measure. Define $\tilde{\varepsilon}_t$ to be a standard Normal random variable under $\tilde{P}$. Then $\tilde{\varepsilon}_t$ is related to ε_t by the relationship

$$\tilde{\varepsilon}_t = \varepsilon_t + \phi_t$$

We can substitute from this expression into (3) to derive the stock price process under the martingale measure

$$\begin{aligned} \ln \frac{S_{t+1}}{S_t} &= r + \frac{1}{2}\sigma_t^2 + \sigma_t \tilde{\varepsilon}_{t+1} \\ \sigma_t^2 &= \beta_0 + \beta_1 \sigma_{t-1}^2 + \beta_2 \sigma_{t-1}^2 \max(0, \phi_t - \tilde{\varepsilon}_t)^2 + \beta_3 \sigma_{t-1}^2 (\tilde{\varepsilon}_t - \phi_t)^2 \end{aligned} \tag{7}$$

where ϕ_t is given by (6). Note that the drift terms α_0 and α_1 are both the present in the risk neutral process for the stock price and therefore will also be present in the option pricing formula. The implication of this is that unlike with the Black-Scholes/Merton pricing formula, the drift of the stock price process enters into the option pricing formula. This dependence is due to of the non-Markov nature of the GARCH process.

As noted earlier the term ϕ_t can be thought of as the market price of risk at time t. Therefore, another crucial difference between this setup and that with geometric Brownian motion for the underlying is that this setup includes a time varying risk premium.

A.3 GARCH-Jump Process

Before we can price the warrants, the issue of how the FDA advisory committee's recommendation will impact the stock price needs to be considered. The announcement of this recommendation represents the sudden release of extremely relevant information to the market and therefore should have a large impact on the valuation of Cephalon's stock as well as its volatility level. The GARCH model we have constructed does not adequately capture this particular shock. To this end, we add a one-point jump term to the stochastic processes for the stock price and volatility. The complete stochastic process for the stock under the martingale measure is therefore given by the Jump GARCH process

$$\begin{aligned} \ln \frac{S_{t+1}}{S_t} &= r - \frac{1}{2}\sigma_t^2 + \sigma_t \varepsilon_{t+1} + J1_{\{t=t^*\}} \\ \sigma_t^2 &= \beta_0 + \beta_1 \sigma_{t-1}^2 + \beta_2 \sigma_{t-1}^2 \max(0, \phi_t - \tilde{\varepsilon}_t)^2 + \beta_3 \sigma_{t-1}^2 (\tilde{\varepsilon}_t - \phi_t)^2 + j1_{\{t \geq t^*\}} \end{aligned} \tag{8}$$

The jump term $1_{\{t=t^*\}}$ on the stock price reflects the large impact that the FDA committee's recommendation will have on the stock price. The jump term has a value of 0, except at time $t = t^*$, when the FDA announcement is made. At this time, the Bernoulli random variable, J, which reflects the magnitude of the jump, takes on a value J_u with probability p or J_d with probability $1 - p$.[6]

In addition, the jump term $1_{\{t \geq t^*\}}$ on the volatility process indicates that the information released will change the unconditional mean of the firm's volatility process. This jump term takes on a value of 0 until time $t = t^*$, at which point it takes on a value of 1 and stays at that value thereafter. The jump magnitude, j, is determined at time $t = t^*$ by a Bernoulli distribution. It takes on a value of j_u with probability p or j_d with probability $1 - p$. The value of j then stays the same thereafter. Thus, the unconditional mean of Cephalon's stock variance is altered from $\frac{\beta_0}{1-\beta_1-\frac{1}{2}\beta_2-\beta_3}$ to $\frac{\beta_0+j}{1-\beta_1-\frac{1}{2}\beta_2-\beta_3}$ at time t^*.

Estimation of the jump parameters cannot be accomplished by using the historical time series of the stock price since the jump term is not present in

[6] Note that these are risk-neutral quantities only and should not be interpreted as the actual parameters governing the jump process.

this series.[7] Therefore, to estimate the jump parameters, we rely on the prices of currently traded options on Cephalon's stock. If these options mature after the date of the FDA committee's decision, then the options incorporate the jump into their prices. Therefore, we estimate the jump parameters by fitting our option pricing model to cross-sectional data on the prices of Cephalon options maturing in August. The pricing model utilizes Monte Carlo simulation with a control variate for variance reduction. The time interval used in the model is daily. The upward jump magnitudes, J_u and j_u, are estimated to be 1.19 and and 0.17, respectively, on May 7, while the downward jump magnitudes, J_d and j_d, are estimated to be 0.64 and 0.25, respectively. We also estimated these quantity one month prior, on April 8, using May options. Since no substantial news was released between the two dates regarding the probability of approval of Myotrophin, we would not expect the jump parameters to be significantly different from each other. This is confirmed as J_u and j_u, for example, are estimated to be 1.23 and 0.18, respectively.

A.4 Dilution Effect of Warrants

The final valuation of the Cephalon options also needs to account for the dilution effect caused by the warrants. In the case of standard warrants, exercising the warrants increases the number of shares of the firm outstanding. Therefore, exercise of the warrants means that the firm's profits are spread out over a larger number of shares, thereby decreasing the value of each share. In Cephalon's case, the dilution effect is caused by Cephalon itself when it exercises the options and therby buys back its own stock. Therefore, one key difference between Cephalon's warrants and standard warrants is that the number of shares of the firm outstanding after the transaction decrease as a result of exercise. Secondly, unlike typical stock buybacks, upon exercise Cephalon will pay the exercise price of \$21.50 per share for stock that has a value higher than \$21.50.[8] Therefore, Cephalon has essentially underpaid for an asset, and the resulting value-added from this underpayment accrues

[7] Actually, it can be argued that the market knows the presence of the future jump shocks and therefore incorporates it into Cephalon's stock price and volatility. However, without a good model for valuing the stock itself, attempting to estimate the jump terms from the stock price series is beyond the scope of this paper.

[8] After all, Cephalon will only exercise the warrants if the stock has a value higher than the exercise price at the maturity date.

to those owning shares in the firm. This serves to enhance the value of all of Cephalon's outstanding shares as well as shares purchased by Cephalon. As a result, the dilution effect for these warrants works in the opposite direction to that of typical warrants. The dilution effect of Cephalon's warrants will add value if the options are exercised.

A.5 Final Valuation

With all of the parameters estimated for the jump-GARCH model, we can now price the Cephalon warrants. The pricing model needs to incorporate three non-standard features about the warrants. First, the payoff on the warrant at expiration is determined by averaging the underlying over the previous twenty days and subtracting off the strike. Second, a cap of $39.50 is placed on this average. Thus, these warrants are essentially capped Asian options. Third, the warrants are exercised by the company against its own stock, so there is a negative dilution effect if the warrants are exercised. The Monte Carlo pricing model used earlier to estimate the jump parameters is modified to account for all of these features.

The price of the Cephalon warrants are calculated to be $3.48 per option.[9] As expected, the cap feature has the biggest impact on the warrant price. Without the cap of $39.50 in place on the underlying, the price of the warrants would have cost $4.98 each. The averaging feature has an insignificant impact on the price because the averaging period is very short, only 20 days. The dilution effect is substantial, adding approximately $.19 to the price of the option. As mentioned above, the dilution effect adds value to the warrant because if the firm exercises the option, it pays $21.50 per share for 2.5 million shares that have a higher value. This enhances the value of the shares purchased.

As indicated in the text, the warrant price derived here differs significantly from the price obtained by simply using the Black-Scholes/Merton

[9] In running the Monte Carlo simulation model, the time interval used is daily, and 200,000 simulations are used to obtain prices. The underlying price is $19.85, which is calculated as in Shimko (1993) by using currently traded August puts and calls and finding the underlying price that best fits with put-call parity. Unlike Shimko (1993), however, the interest rate is not calculated through this method, but instead, the 6 month yield of 5.5% per annum is used. Finally, the initial volatility is calculated from the estimates of the GARCH model to be 5.3% per day on May 7. The estimated upward jump magnitude, j, is .307, with a corresponding jump probability of 42.4%, which were calculated as described above.

model naively. Because the model we have used captures much of the complexity of the transaction as well as the nonlinearities in the data, we feel this price discrepancy is an indication of the error produced when using the Black-Scholes/Merton model in cases where its underlying assumptions are clearly not met. Therefore, we feel that when such nonlinearities as stochastic volatility and the one-point jump process are present, it is important that they be incorporated into pricing models.

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